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CHEMICAL AND MINERALOGICAL CHARACTERISTICS OF SOME SOLONETZIC SOILS IN RELATION TO THEIR GENESIS

by

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A THESIS

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The undersigned certify that they have read, and recommend to the Faculty of Graduate Studies for acceptance, a thesis entitled "Chemical and Mineralogical Characteristics of Some Solonetzic Soils in Relation to Their Genesis", submitted by Muhammad Ahmad Arshad, B.Sc. (Agri.), M.Sc. (Agri.), in partial fulfilment of the requirements for the degree of Doctor of Philosophy.

ABSTRACT

Seven profiles of Solonetzic and associated soils were sampled from the Black zone near Edmonton, Alberta. Physical, chemical, and mineralogical investigations were carried out on these samples with the object of studying the degree and the nature of pedogenesis in these soils. The more significant findings and conclusions follow:

The maximum levels of soluble salts which are dominantly sodium sulphate and magnesium sulphate occur in the Black Solonetz, with lesser amounts in the Black Solodized Solonetz and the least in the Eluviated Black soils. Generally, the maximum soluble salt content and the fine clay content occur together in the lower B or upper C horizons of the profiles studied. The movability of the fine clay has been considerably reduced in horizons where the concentration of soluble salts exceeds a critical minimum limit. This limit appears to lie between the electrical conductivity values of 2 and 3 mmhos/cm. for these soils.

The exchangeable cation characteristics of the various horizons reflect some noteable effects. The B horizons of the profiles, classified as Solonetzic soils, contain the maximum percentage of exchangeable sodium varying from 14.3 to 40.6. The high content of exchangeable sodium appears to have aided in the comminution of coarse particles and caused a substantial increase in particles of fine clay size in these horizons. High exchangeable magnesium in the soils where solonetzic processes were weak or absent probably resulted from the

replacement of exchangeable sodium by the magnesium cation in soil solution during the early stages of solodization which was initially active in these profiles. Similar displacement appears to have occurred in the soil which was more or less completely solodized. The maximum exchange acidity occurs in the solodized horizons where a considerable portion of the acidity is contributed by the hydrogen released during the hydrolysis of exchangeable aluminum ions.

Mineralogical data indicate that montmorillonite is the dominant clay mineral while illite and kaolinite are next in abundance in all profiles except in the Ae horizon of the completely solodized profile where kaolinite is approximately equal to montmorillonite. The montmorillonite was identified as being transitional between beidellite and nontronite types. Chlorite and interstratified minerals are also present in trace amounts in some horizons. The lower illite content and higher montmorillonite content in B horizons as compared to A horizons indicate the preferential translocation of montmorillonite. Degradation of illite is evident in horizons which have undergone solodization. These facts suggest that during solodization some of the clay colloids had undergone chemical transformation as well as physical translocation.

The study of light minerals, which form the major portion of primary minerals in these soils, show some weathering of feldspars which is most apparent in the solodized (Ae) horizons

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INTRODUCTION

Solonetzic soils commonly occur in the arid and semi-arid regions of the world. They may also occur in poorly drained depressions of humid regions. These soils are formed as a result of the specific pedogenic processes -- solonization and solodization. These processes may characterize not only soils developed through geologic time, but also those soils which have been strongly influenced by the activity of man, particularly in the field of irrigation which plays a major role in changing the morphology and chemical nature of these soils.

Solonetzic soils are of common occurrence throughout the post-glacial Edmonton laking basin. Slight variations in the degree of drainage have lead to the development of different groups of Solonetzic soils. This situation affords an excellent opportunity to study these soils in relation to their pedogenic development.

The present day views on the genesis of Solonetzic soils are mainly based on the concepts originally outlined by early Russian workers. Gedroiz is recognized as one of the most outstanding investigators, having made basic contributions to our knowledge of the genesis of these soils.

Evolution of Solonetzic soils as presented by various workers may be explained through various stages in their development. In the Canadian Soil Classification Scheme (1963) three such stages are recognized: Solonetz, Solodized Solonetz, and Solod. These stages are believed to develop from a group of soils called Solonchaks or Saline Regosols which contain an

appreciable quantity of sodium ions. Solonchak soils or Saline Regosols are formed as a result of an accumulation of excessive amounts of soluble salts in the surface layers. This process of salt accumulation is termed salinization. Enormous differences in the morphological and chemical characteristics may develop if the soluble salts are leached as a result of improved drainage conditions. Solonchaks subjected to leaching become highly dispersed if they contain at least 12 to 15 per cent of sodium on the cation exchange complex. The dispersed soil becomes fissured upon drying into definite structural entities, the characteristic of which is the strong columnar structure in the B horizon. This process of change is called solonization and the resulting soil with a distinct morphology is referred to as Solonetz.

After prolonged leaching of a Solonetz, the surface horizons become more acidic and a deep, well defined light coloured siliceous eluviated horizon (Ae) overlying a blocky and mildly acidic B horizon develops. A strong platy structure of the eluviated horizon is a distinct feature of these soils. These soils represent the final stage in the evolution of Solonetzic soils and are called Solods. The process that transforms a Solonetz to the Solod stage is called solodization.

A number of Solonetzic soils in Western Canada as well as in other areas of the world are not completely solodized. These soils have the well developed light coloured and acidic eluviated horizon of the Solod and the alkaline columnar B horizon of the Solonetz. This group of soils is designated as Solodized Solonetz and is considered to be a transitional stage between the Solonetz and the Solod.

In spite of the fact that extensive literature exists on Solonetzic soils, full understanding of their genesis is still lacking. The general trend in the studies over the past several years has been concerned with an understanding of the characteristics and cultural aspects of these soils rather than their genesis. Little work has been done in the study of mineralogical weathering as related to the pedogenic processes concerned in their development. There are few data which relate to the stability of clay minerals undergoing solodization. As an example, some workers have reported that the illuvial clay is more pronounced in the B horizon of a Solodized Solonetz than a Solonetz soil. However, critical examination of these data show that the illuviated clay in the lower horizons does not completely account for the total amount of clay disappearing from the surface horizons. The mineralogical investigations on these soils have not advanced to a stage where soil scientists can provide an appropriate solution to such pedological problems. A thorough study of the mineralogical weathering, both of the clays as well as the primary minerals, is needed to support the theoretical explanations proposed by various workers. This type of study is required in order to gain a better understanding of the genesis of these soils and to assess more scientifically the validity of the original concepts outlined by early Russian workers.

Thus the main objectives of this study were:

1. To study the extent and the nature of mineralogical weathering proceeding in the major horizons of some Solonetzic soils of Alberta in relation to their genesis.

2. To elucidate some of the mechanisms involved in the formation and degradation of solonetzic B horizons.
3. To clarify some of the contradictory opinions held by the previous workers as they relate to the genesis of Solonetzic soils.

REVIEW OF LITERATURE

Geographical Distribution of Solonetzic Soils

Solonetzic soils in their varying degree of development are known to occur in various climatic zones of the world, particularly in areas where precipitation is relatively low.

It has been estimated that there are over ten million acres in Alberta where Solonetzic soils are either continuous or form not less than 20 per cent of a mixture within a mapping unit (Odynsky, 1945). As reported by Bowser (1961), the three largest areas of Solonetzic soils in Canada are: the level plain between Avonlee, Weyburn, and Estevan in Southeastern Saskatchewan; a shallow till to modified bedrock area immediately north of the International Boundary on the Saskatchewan-Alberta border; and a relatively level area of shallow ground moraine extending some three hundred miles from Vegreville to Taber in Alberta. Smaller areas occur in the lacustrine clays of the Red River Valley and the till plain north of Virden, both in Manitoba, the Kerrobert area in Saskatchewan, in the Wetaskiwin-Edmonton-Westlock area of Alberta, and in the Peace River area.

Solonetzic soils are found in many western states of the United States. Fehrenbacher *et al.* (1963) reported their occurrence in South-central Illinois where they occupy more than 381,000 acres. They are also known to occur in Colorado, Montana, Utah, Oregon, Washington, South-central Indiana, California, South Dakota, and a part of the Red River Valley in Minnesota (Kelley, 1951; Kellogg, 1934; Nikiforoff, 1937; Rost, 1936; Rost and Maehl, 1943; Whittig, 1959; and White, 1961).

In South America Solonetzic soils occur in the campos of Brazil, the pampas of Argentina and Patagonia, and on the deserts of the high plateau of Peru and Chile (Glinka, 1927). According to Stelzner (quoted by Glinka, 1927) salt crusts and efflorescences are formed during the dry season (April to September) when the loess soils of the pampas are bare or covered only with a sparse vegetation. The crusts may attain a thickness of a few millimeters. Areas covering several square miles in extent glisten as though covered with snow.

According to Glinka (1927) salt-affected soils are distributed in Europe in the Iberian Peninsula, Southern France, Rumania, Southern and Southeastern Russia up to the northern limits of the Chernozems in the eastern part of Northern Caucasia and the eastern part of Transcaucasia.

Solonetzic soils are known to occur in Asiatic Russia, China, Bokhara, the Arabian Peninsula, Persia, Asia Minor, in the deserts and desert steps of Manchuria, Russian and Chinese Turkestan, and Hindustan (Kelley, 1951). In India and Pakistan they are known by the natives as "Thur", "Sem", "Reh", and many other names. On the shores of the Arabian Sea and along the Indus River they cover a large area and stretch from the latter to the Ganges. From the Gulf of Cutch these soils extend northwestward as far as Afghanistan.

Popazov (quoted by Bernstein, 1962) reported that Solonetzic soils account for 3.4 per cent of the land-area of the U.S.S.R. or more than 75 million hectares. These soils occur in scattered spots of various sizes varying from a few meters to

several hundred meters across, within large tracts of steppe soils. They are more frequent in the zone of semi-deserts, among light-chestnut soils and less common in the desert zone. These soils are usually found in well defined, flat hollows, with a relative depth from a few centimeters to several decimeters; but they may also occupy micro-elevations.

Szabölcs (1962) estimated that salt-affected land in Hungary occupies over half a million hectares. The Hungarian Great Plains is a basin surrounded by mountains in which soil alkalization has been active. Syun (quoted by Bernstein, 1962) stated that 20 million hectares of land in China are salt-affected. Yugoslavia has more than half a million acres of salt-affected land (called "slatina") occurring mostly in slight depressions and areas with high water tables (Miljkovic et al., 1959).

A rather typical Solonetzic area, 200 miles southwest of Brisbane, Australia, is described by Isbell (quoted by Bernstein, 1962). This almost level area of 10,000 acres lies over a perched water table that fluctuates and at times approaches the soil surface.

In Africa the Sahara and its northern boundary regions contain numerous alkali soils. They are also found in the deserts and semi-arid regions of Southern Africa (Glinka, 1927).

From the above survey of literature on salt-affected soils it is clear that the Solonetzic soils occupy a considerable portion of the productive land of the world, especially of arid zones.

Classification of Solonetzic Soils

Systematic classification of Solonetzic soils has been and still is a subject of wide discussion among many soil scientists. In the United States, Hilgard (1918) was one of the first to attempt a system of classification. He classified the alkali soils purely on the basis of their agro-chemical features. Since then, numerous classification systems have been attempted in various parts of the world. The classification systems of salt-affected soils that are most frequently described in the literature are:

I. The Hilgard system.
II. The Hungarian system.
III. The Russian system.
IV. The U.S. Salinity Laboratory system.
V. The U.S.D.A. system.
VI. The Canadian system.

I. The Hilgard System of Classification

Hilgard divided salted soils into two main groups, namely: (1) white alkali and (2) black alkali.

White alkali soils contain various proportions of NaCl, Na_2SO_4, $CaCl_2$, $MgCl_2$, occasionally borates, and nitrates. These salts form a white crust on the surface of the soil in dry periods.

The term black alkali applies to soils rich in Na_2CO_3 which produces a highly alkaline reaction and causes a dispersion of both inorganic and organic colloids. Under such conditions the organic matter present becomes soluble and the latter is

deposited lower in the profile as a thin film on the surfaces of the soil peds.

This system was primarily based on agro-chemical rather than genetic features.

II. The Hungarian System of Classification

De Sigmond (1938) in his book "Principles of Soil Science" subdivided sodium (Solonetzic) soils into the following five main types:

1. Saline Soils.
2. Salty Alkali Soils.
3. Leached Alkali Soils.
4. Degraded Alkali Soils ("Soloti Soils").
5. Regraded Salty Alkali Soils.

1. Saline Soils are soils which have an excessive amount of soluble salts, particularly sodium salts, in their surface horizons. The morphology of a saline soil usually resembles that of the original soil or may be entirely structureless. The chemical characteristics of these soils are determined primarily by the kind of water soluble salts present. The bulk of the salts, as reported by de Sigmond (1938), are sodium together with a variable quantity of magnesium salts. The anions occurring most frequently are Cl^-, $SO_4^=$, and $CO_3^=$. These soils correspond to Solonchaks in the Russian and U.S.D.A. classification and Saline Regosols in the Canadian soil classification.

2. Salty Alkali Soils are characterized by a high proportion of exchangeable Na^+ (12 per cent of the total exchangeable cations) associated with a large amount of water-soluble

sodium salts (> 0.2 per cent). Morphologically these soils have faintly developed eluvial and illuvial horizons but not as distinct as in the Leached Alkali soils.

3. Leached Alkali Soils have a definite structural morphology resulting from intense leaching of water-soluble salts from the soil profile. They are easily distinguished by the presence of a hard illuvial horizon (B) below the surface horizon. The B horizon has a well developed columnar structure and is impervious to both water and air, separating off, almost hermetically, the upper horizons of alkali profiles from the lower horizons. These soils may be considered the approximate equivalent of Solonetz soils in other classification systems.

4. Degraded Alkali Soils ("Soloti Soils") result from further leaching of alkali soils. These soils have a thick A horizon which can be subdivided into an upper A1 and lower A2 sub-horizons. The columnar structure of the B1 horizon breaks up into nut-like clods. In the sub-soil one often finds iron gley horizons which mark the levels of the movement of the water table. These soils almost correspond to Solods in other soil classifications.

5. Regraded Salty Alkali Soils are essentially saline soils which have formed from Leached and Degraded Alkali soils that have been subsequently resalinized by a rise in the water table. The profile morphology of these soils may become less distinct than in the original alkali soils by the intrusion of the salty solutions, but the characteristic structure is still discernible. Regradation as a result of rise in the water table

is said to be widespread in Hungary (Arany, 1956, quoted by Bernstein, 1962).

Later, other workers in Hungary classified the salted soils on a basis similar to the original concepts. Arany (1956) classified saline soils of Hungary into alkali-saline, saline-alkali, leached, acid, and regraded types. Szabolcs and Jasso (quoted by Bernstein, 1962) classified "szik" (alkali) soils of Hungary into six types: solonchak, solonchak-solonetz, meadow solonetz, steppe-like meadow solonetz, solod, and solonetzic meadow soils. The main criteria used as a basis of this classification were the nature and amount of salts present, the thickness of the A horizon, and the depth of the calcium carbonate layer.

III. The Russian System of Classification

Many systems of soil classification have been proposed in the U.S.S.R. by various soil scientists. Despite all the systems proposed starting from Dokuchaiev (1886) up to the latest one presented by Ivanova and Rozov (1960) at the 7th International Congress of Soil Science, none have been completely satisfactory. However, from the list of U.S.S.R. soils established by the Soil Institute of the Academy of Sciences, U.S.S.R., the following types have been described (Rode, 1962) in Russian literature:

1. Solonchak (Saline Soils).
2. Takyr Soils.
3. Takyr-like Soils.
4. Solonetz Soils.
5. Solod Soils.

1. Solonchaks (Saline Soils) are soils that contain more than one per cent soluble salts in their uppermost layer. Morphologically these soils are structureless. The degree of salinity present in these soils is expressed in terms of the amount of salts present and the depth of the salt-bearing horizon. According to Rode (1962) a soil is considered non-saline if it contains less than 0.25 per cent easily soluble salts (up to a depth of 150 cm.). If salts, in amounts greater than 0.25 per cent by weight of soil, occur between depths of 80 and 150 cm., the soil is called weakly-solonchakous; if they occur within the depth limits of 30 and 80 cm., the soil is solonchakous; if the salts occur between 5 and 30 cm., the soil is solonchakic. When the uppermost layer contains more than one per cent salts, the soil is called solonchak.

2. Takyr Soils as described by Bazilevich (1956, quoted by Bernstein, 1962) have a non-saline layer of 10 to 30 cm., underlain by a strongly saline horizon containing a minimum of 2 per cent salts. Rode (1962) reported that Takyr soils in the U.S.S.R. are found within the flat micro-depressions of the desert zone. These soils are almost bare of vegetation except for some films of blue-green algae which usually occur on the surfaces. The extreme flatness of this surface is a very characteristic feature of Takyrs. The crust is dissected by deep wide cracks into a polygonal pattern of various sizes. The profile of Takyr consists of the spongy-porous crust, from 1 to 8 cm. thick, criss-crossed with fissures, and has an underlying horizon with a flaky structure. Gypsum is frequently present in high concentrations at depths of 2 to 3 feet.

3. Takyr-like Soils represent the early stages of Takyr soil development. The characteristics of Takyrs are weakly expressed in these soils.

4. Solonetz Soils may have a top horizon which varies in thickness from 2 to 3 cm. and is called "crusty Solonetz" or 15 to 25 cm. which is referred to as "deep-columnar Solonetz". This horizon is light grey, with dark tinges, depending on the humus content. It usually has a laminar structure but sometimes this horizon is slightly cemented forming a brittle thin crust of spongy or porous constitution. The top horizon is underlain by an illuvial B horizon with columns, stubs, or prisms as structural units. The tops of the columns are usually somewhat rounded. Such columns break up into well defined cuboidal units with flat facets which are rather shiny and are dark brown or brownish-black in colour. The solonetzic horizon is underlain by a horizon of salt accumulation with a thickness varying from 50 to 300 cm. Solonetz soils often contain calcium carbonate which occurs in the middle or lower part of the columnar horizon. The thickness of this horizon may reach one meter.

Solonetz soils in the U.S.S.R. are highly diversified in profile structure and chemical composition and have been further subdivided in their classification. The following criteria have been used for their further subdivision:

(a) Depth of the water table: (1) meadow Solonetz are soils with a water table not deeper than 5 m.; (2) meadow steppe Solonetz have water tables between 5 and 8 m.; and (3) steppe Solonetz have ground water at depths below 8 m.

(b) Thickness of the top horizon above the Solonetz layer: (1) shallow Solonetz soils have an upper horizon not thicker than 7 cm., including crusty Solonetz where such horizons are not more than 3 cm.; (2) medium columnar, where the upper horizon is from 7 to 15 cm. thick; and (3) deep columnar, where this thickness varies from 15 to 25 cm.

(c) Depth of bedding of salts: (1) Solonchakic Solonetz have salts bedded from a depth of not more than 30 cm.; (2) Solonchakous Solonetz have salts at depths 30 to 80 cm.; and (3) deep Solonchakous Solonetz have salts at a minimum depth of 80 cm.

(d) In accordance with the composition of salts, they are subdivided into: (1) soda-Solonetz; (2) Solonetz soils with mixed salinity (soda-chloride-sulphate); and (3) soils with chloride-sulphate salts.

5. Solod Soils are soils with a humus horizon varying from 6 to 10 cm. in thickness, underlain by a whitish solodized horizon which is structureless but often may contain a remnant structure of the former columns of the solonetzic B horizon. The thickness of this solodized horizon may reach 10 to 20 cm. It often contains many concretions of sesquioxides. Underneath the solodized horizon there is an illuvial horizon which may have residual columnar structure. The lower portion of this horizon is often calcareous. The upper horizons of Solods usually have weakly acid reactions.

IV. U.S. Salinity Laboratory System of Classification

The U.S. Salinity Laboratory Staff (1954) divided the salted soils into three groups:

1. Saline Soils are soils for which the conductivity of the saturation extract is more than 4 mmhos/cm. at 25°C. and the exchangeable sodium percentage (ESP) is less than 15. Ordinarily, the pH is less than 8.5 .

2. Saline-Alkali Soils are soils for which the conductivity of the saturation extract is more than 4 mmhos/cm. at 25°C. and the exchangeable sodium percentage is greater than 15. Under conditions of excess salts, the pH is seldom higher than 8.5.

3. Non-Saline-Alkali Soils are soils for which the conductivity of the saturation extract is less than 4 mmhos/cm. at 25°C. and the exchangeable sodium percentage is greater than 15. The pH usually ranges between 8.5 and 10.

The criteria used for separating the various groups in this classification are considered to correlate with the productivity of the soils. For instance, the high amounts of soluble salts in the case of saline soils impair the productivity of the soils for the growth of common agricultural crops. Similarly, a high percentage of exchangeable sodium in the case of non-saline alkali and alkali soils has a similar effect.

V. The U.S.D.A. System of Classification

In the U.S. soil classification by Baldwin et al. (1949, first published in 1938), the salted soils have been subdivided

into the following three Great Groups within the Intra-zonal soils:

1. Solonchak or Saline Soils.
2. Solonetz Soils.
3. Soloth or Solod Soils.

1. Solonchak or Saline Soils. This group of soils is characterized by the presence of an abnormal quantity of soluble salts which are distributed throughout the profile. There is no specification as to the chemical nature of the salts. Horizon differentiation in a Solonchak profile is negligeable. These soils resemble the Saline Regosols of Canada or the Saline soils described by the U.S. Salinity Laboratory Staff.

2. Solonetz Soils. These soils are distingusihed by the presence of a columnar structure in the B horizon. The sides of the structural units are coated with organic and inorganic colloids to give them a nearly black colour. The A2 horizon is thin but has a well defined grey colour and platy-vesicular structure. Reaction of the profile varies from near neutral in the surface to more than 8.6 in the B horizon. Sodium saturation is more than 15 per cent in the B horizon and there is a lime zone present in the lower B2 or B3 horizons. Remnants of salts in the B3 or the C horizon are commonly encountered. These soils may or may not correspond to Russian Solonetz. It may be mentioned that the Russian Solonetz do meet the required characteristics of American Solonetz but the American Solonetz may not have any place in Russian Solonetzic soils.

3. Solod Soils. Continued leaching of a Solonetz soil is presumed to effect the development of a Solod, as an end-member in a time sequence. The criteria used in the recognition of Solod soils are: generally grey colour of the entire surface layer which has a platy structure; the A1 horizon is either absent or very thin; the upper solum is acid, but calcium carbonate may be present in the lower part of the profile; sodium saturation percentage is low throughout the soil; and soluble salts are almost absent from the solum.

According to some workers (U.S. Soil Survey Staff, 1951), a great many soils in the United States are transitional between Solonetz and Solod. Most of these soils have acid A horizons and very slightly acid to strongly alkaline B horizons with well developed columnar structures. These soils are called solodized-Solonetz -- a term first introduced by Kellogg (1934). However, solodized-Solonetz soils were never considered an independent group in the U.S. classification of Solonetzic soils.

In a new U.S. classification of soil, the 7th approximation, an attempt is made towards a natural system of soil classification. The Solonetzic soils have been placed into five orders, namely: Entisol, Vertisol, Aridisol, Mollisol, and Alfisol. Since the criteria used in establishing the various categories in this new soil classification system are quite different in comparison to the old system (i.e., 1949 system), the exact equivalents for Solonetzic soils cannot be given here. However, the approximate equivalents are listed in Table I.

TABLE I. Solonetzic Soils in the American Classification, 7th Approximation, and Their Approximate Equivalents in Canadian Soil Classification

Order	Sub-order	Great Group	Sub-group	Approximate Equivalent in Canadian Classification
1. Entisol	1.1 Aquent	Undefined	Undefined. Aquents (with natric horizon) which are saturated with water at some season or that have been artificially drained. Sodium saturation of more than 15 per cent in the surface and decreasing saturation with depth below 20 inches.	Gleyed Saline Regosol
2. Vertisol	2.1 Aquert	2.12 Mazaquert	2.12-5.35. Natraquollic Mazaquert have surface horizon 12 inches or more thick with moist colour values as dark or darker than 3.5 and dry values as dark or darker than 5, and that have more than 15 per cent extractable sodium in some part of the upper 12 inches.	None
			2.12-7.16. Natraqualfic Mazaquert have surface horizon lighter in colour than 3.5 moist, or 5 dry or less than 12 inches if darker and have 15 per cent or more extractable sodium in some part of the upper 12 inches.	None

(Continued)

TABLE I. (Continued)

Order	Sub-order	Great Group	Sub-group	Approximate Equivalent in Canadian Classification
	2.2 Ustert	2.22 Mazustert	2.22-7.42. Natrustalfic Mazusterts are usually moist and have 15 per cent or more extractable sodium within some part of the upper 12 inches. The soils of this group most often are in a Mediterranean climate and are not known to exist in the U.S. at present time.	None
			2.22-4.23. Natrargidic Mazusterts. The characteristics of this sub-group are similar to that of Natrustalfic except that they are dry.	None
3. Inceptisol	3.1 Aquept	3.11 Halaquept	Sub-groups are not defined. The Halaquepts with 15 per cent or more extractable sodium in the surface horizon and with sodium saturation decreasing with depth below 20 inches. This group is provided temporarily and may not fit within Inceptisols.	Alkali Solonetz in 1960 Canadian Soil Classification

(Continued)

TABLE I. (Continued)

Order	Sub-order	Great Group	Sub-group	Approximate Equivalent in Canadian Classification
4. Aridisol	4.1 Orthid	4.14 Salorthid	No sub-groups are proposed. The Salorthids have a salic horizon at a depth of less than 20 inches. When dry they usually have a thin or thick salt crust at the surface. Vegetation is sparse or salt loving.	Saline Regosols (Solonchaks in U.S.D.A. 1949 soil classification)
	4.2 Argid	4.23 Natrargid	No sub-groups are proposed. The Natrargids have an ochric epipedon and a natric horizon. They may be usually moist. The conductivity of the saturation extract must be 1 mmho. or more at some depth. The carbonates in the A and in the natric horizon are typical, as is the increase in organic matter in the natric horizon.	Brown Solonetz
		4.24 Nadurargid	No sub-groups are distinguished. The Nadurargids have an ochric epipedon and have a natric horizon as well as a duripan. The duripan does not soften in acid, though it is usually partially cemented with calcium carbonate.	None

(Continued)

TABLE I. (Continued)

Order	Sub-order	Great Group	Sub-group	Approximate Equivalent in Canadian Classification
5. Mollisol	5.2 Alboll	5.22 Natralboll	The sub-groups are characterized on the properties of the upper sequum. The Natralbolls have a mollic epipedon, an albic horizon, and a natric horizon, in that sequence. Ruptic intergrades are probable in this great group because the albic horizon tends to be discontinuous. The exchangeable sodium may be low in the natric horizon if exchangeable magnesium and sodium exceed calcium and hydrogen. However, the soils with large amounts of magnesium in the natric horizon must have more than 15 per cent saturation with sodium in some horizon or layer below the natric horizon.	Solodized Solonetz to Solod depending upon the degree of profile development. Further subdivisions into sub-groups depend upon the colour of the surface horizon.
	5.3 Aquoll	5.35 Natraquoll	(Tentative great group) Aqualls with natric horizon but most of the soils may be ruptic intergrades with Natralbolls.	Gleyed Solonetz
	5.4 Altoll	5.42 Haplaltolls	5.42-5.45. Natric Haplaltolls. This sub-group includes soils that have an albic and a natric horizon underlying the cambic horizons. These soils are not identified in the U.S.	None

(Continued)

TABLE I. (Continued)

Order	Sub-order	Great Group	Sub-group	Approximate Equivalent in Canadian Classification
		5.45 Natraltolls	No sub-groups are proposed. The great group includes Altolls that have a natric horizon in or below the epipedon but have no intervening cambic horizon. There may be a thin albic horizon.	Black Solonetz and some Black Solodized Solonetz with thin albic horizons.
	5.6 Ustolls	5.66 Natrustolls	No sub-groups are defined. The great group includes Ustolls that have a natric horizon. The mollic epipedon often includes a thin albic horizon that lies entirely within the upper 7 inches.	Some Brown and Dark Brown Solonetz and Solodized Solonetz with thin albic horizons.
7. Alfisols	7.1 Aqualf	7.15 Natraqualf	No sub-groups are proposed. The Natraqualfs are the Aqualfs that have a natric horizon. In some the only apparent source of the sodium is weathering of feldspars.	Gleyed Solodized Solonetz
	7.2 Altalf	7.23 Natraltalf	No sub-groups are proposed. The great group includes Altalfs that have a natric horizon. The soils have not been identified in the U.S.	Dark Grey or Grey Wooded Solods and Solodized Solonetz.

(Continued)

TABLE I. (Continued)

Order	Sub-order	Great Group	Sub-group	Approximate Equivalent in Canadian Classification
	7.4 Ustalf	7.42 Natrustalf	No sub-groups are proposed. The Natrustalfs include the Ustalfs with a natric horizon. They have often Ca horizons and may have duripans like those of Durustalfs. They are rare in the U.S.	None

VI. The Canadian System of Classification

The National Soil Survey Committee of Canada (1963) characterized Solonetzic soils by the presence of solonetzic or disintegrating solonetzic B horizons. These horizons have an exchangeable base status in which 50 per cent or more of the exchangeable ions are sodium plus magnesium or have more than 12 per cent exchangeable sodium, and usually have saline sub-soils. The solonetzic B horizons are characterized by coated columnar or prismatic macrostructures and blocky micro-structures, with hard to very hard consistence when dry.

The Solonetzic Order is classified into three Great Groups: Solonetz, Solodized Solonetz, and Solod. The degree of development of Ae and B horizons has been used as a basic criterion to separate the various groups.

1. Solonetz. These soils have an Ah horizon which may be underlain by a thin weakly expressed and slightly lighter coloured Ahej horizon. A thin Ae horizon may be present in soils intergrading to Solodized Solonetz. The solonetzic B horizon (Bnt) is well developed and has a columnar structure with a moderately hard consistence when dry. The reaction of the Bnt horizon varies from weakly acidic to slightly alkaline. The upper C horizon is usually slightly saline and calcareous. These soils resemble the Solonetz soils of the United States and the Leached Alkali soils in de Sigmond's classification of Solonetzic soils.

2. Solodized Solonetz. These soils are characterized by the presence of an Ah horizon or with a very thin Ahj horizon

overlying a lighter coloured Ae horizon. The Ae horizon has a strongly developed platy structure and is significantly lighter in colour than the B horizon. The Bnt horizon is solonetzic with a very hard white-capped columnar macrostructure, the latter usually making a sharp interface between the friable Ae and hard Bnt horizons. The surfaces of the aggregates, which are strongly coated, have a darker colour than the inside of the peds. The B horizon is slightly acidic to moderately alkaline. The lower B and C horizons are normally alkaline and frequently saline.

3. Solods are soils with an Ah horizon which is usually thinner than the light coloured Ae horizon. The Ae horizon is well developed and may frequently be divided into Ae1 and Ae2 sub-horizons. The lower portion of the Ae (Ae2), if present, is lighter in colour and more acidic than the Ae1 and has a stronger development of platy structure. There is no abrupt or sharp interface between the Ae and B horizon. A transitional AB horizon expressing disintegration of the upper part of the solonetzic B horizon is a distinct characteristic of this group. The Bnt horizon may be relatively thin and may only have weak prismatic structure breaking easily to blocky aggregates. The C horizon is usually saline and calcareous.

Morphological Characteristics of Solonetzic Soils

Morphological characteristics have been considered to be of prime importance in almost all the classification systems attempted to date throughout the world. According to

early Chinese records, a classification of soils based on their colour and structure (morphology) was developed by the engineer Yu during the reign of the Emporor YaO about 4,000 years ago.

Morphological characteristics of soils, to a considerable extent, reflect the effects of local and zonal soil forming agents. The recognition of Solonetzic soils, in their various stages of development, is largely based on morphological features.

Solonchaks are distinguished by the presence of high amounts of soluble salts in the surface layers. They are light in colour, flocculated and often are structureless. They lack horizon differentiation (Joffe, 1949; Bowser, 1961). Some workers (U.S. Soil Survey Staff, 1951) describe these soils as soft and fine granular but characteristically lack both prismatic and blocky structure.

The characteristic morphological features given for a classical Solonetz are: the presence of a compact solonized B horizon distinguished by a columnar structure with a moderately hard consistence; the tops of the columns are usually flat, sometimes slightly rounded as a result of the development of a thin light coloured Ahej sub-horizon (Muratova, 1959; Bowser, 1961). Odynsky (1945) describing the Solonetzic soils in Alberta stated that these columns are usually about 1 to 2 inches wide and rarely more than 8 inches in height. The structural units of these columns are coated with a dark shiny film imparting to them a glazed appearance. The sub-horizon B2 is usually lighter in colour than the B1 and often mottled.

The salt accumulation in Solonetzic soils is ordinarily observed in the lower B horizons, sometimes at a considerable depth. According to Muratova (1959) there are types of Solonetz soils where a high accumulation of salts is noted in the compact upper B horizon. These soils have been referred to as Solonchak-like Solonetz. Their distinctive features are: strong salinization of the soil profile, calcareous surface horizons, weak differentiation of the soil profile, and indications of excessive moisture in the lower horizons.

Solodized Solonetz is characterized by a light coloured Ae horizon with a strongly developed platy structure and a very friable consistence. The thickness of this horizon (Ae) varies with the degree of development. The hard columnar B horizon has white-capped round tops. The faces of the columns are not as dark coloured as in the Solonetz due in part to a coating of silica grains washed down from the saliceous horizon above. Below the columnar B horizon there is usually a compact horizon with a poorly defined structure that is transitional to the horizon of lime and salt accumulation (Kellogg, 1934; Bowser, 1961). Frequently, the leached surface layer of Solodized Solonetz is eroded away exposing the hard clay of the B horizon in the bottoms of shallow pits. Such soils are called truncated Solodized Solonetz (U.S. Soil Survey Staff, 1951).

The Solod has a deep grey horizon (Ae) which is usually thicker than the overlying Ah horizon. The vestiges of former columnar B horizons may often be recognized in the upper solodized horizons. The C horizon is usually saline and calcareous (Rode,

1962; U.S. Soil Survey Staff, 1951; National Soil Survey Committee, 1962).

From the literature cited above, it is evident that considerable emphasis has been placed on the morphological characteristics in differentiating the Solonetzic soils.

Chemical and Physical Characteristics of Solonetzic Soils

Hilgard (1918) suggested that the salts present in North American Alkali (Solonetzic) soils vary greatly in their composition but that NaCl, Na_2SO_4, and $NaHCO_3$ predominate. In the presence of $NaHCO_3$ (soda), Na_2SO_4 and NaCl are generally absent or occur only in small amounts. In areas where Na_2SO_4 and NaCl predominate, $NaHCO_3$ is usually absent. The composition of soluble salts in Russian Solonchaks is similar to that of many alkali soils of the United States (Kelley, 1951).

Accumulation of a considerable amount of soluble salts which are strong electrolytes results in the coagulation of all soil colloids. Therefore, the alumino-silicate constituents remain inert and are not subject to transformations (Rode, 1962). The composition of exchangeable cations in Solonchaks depends largely upon the composition of salts. The exchange capacity varies within wide limits, depending upon the texture of the soil. The pH value in a Solonchak rarely exceeds 8.5 (Russell, 1961). These soils remain permeable.

One of the criteria used in the recognition of Solonetz soils in Canada and the United States is that the B horizons

of these soils contain more than 15 per cent exchangeable Na^+. However, many Solonetzic soils in Canada show typical morphological characteristics of a Solonetz but lack Solonetz chemistry (MacGregor and Wyatt, 1945). Ehrlich and Smith (1958) reported that in the principal horizons of 11 halomorphic profiles water soluble Na^+ was equal to or greater than water soluble Ca^{++} or Mg^{++}. However, exchangeable Na^+ in excess of 15 per cent of the exchangeable cations was found only in some horizons of Solonchak, Solonetz, and Solodized Solonetz soils.

Vedenicharov (1959) reported that a characteristic feature of the Solonetzic soils in Bulgaria is the high content of $NaHCO_3$ and Na_2CO_3 which are found in large concretions even in the deep horizons. Exchangeable Na^+ content varies from 80 to 90 per cent of the total cation exchange capacity. Isbell (quoted by Bernstein, 1962) reported that exchangeable Na^+ in Solonetzic soils of Brisbane, Australia ranges from 14 to 33 per cent in the A1 and A2 horizons and 34 to 46 per cent in the B horizons. Bowser et al. (1962) reported that the B horizons of Solonetz and Solodized Solonetz soils contain over 15 per cent exchangeable Na^+. The C horizons were quite saline, the principal salt being Na_2SO_4.

Reiken and Stalwick (1945) stated that low permeability, relatively high dispersion, and low aggregate stability in the B1 horizon of Solonetz soils are closely associated with the high Na^+ saturation of the exchange complex.

Numerous workers (Ellis and Caldwell, 1935; Ehrlich and Smith, 1958; Bentley and Rost, 1947; Reiken, 1943; Rost, 1936;

Rost and Maehl, 1943) reported a high amount of exchangeable Mg^{++} in B horizons of soil profiles that show typical solonetzic features. Uzakov (1961) stated that soils with an enhanced content of $MgCO_3$ and adsorbed Mg^{++} are highly compact; they have Takyr-like block disintegration which is cloddy, prismatic, or columnar in the surface horizons. These soils are similar to Solonetz soils in their morphological and chemical properties.

According to many workers (quoted by Uzakov, 1961) Mg^{++} increases the dispersion of soils, reduces the level of micro-aggregation and porosity, and produces a considerable compaction in the dry state. The effect of Mg^{++} on the physico-chemical properties of soil, to some extent, is similar to that of Na^{+}.

Further solodization of Solodized Solonetz soils to a Solod stage causes some distinct changes in the profile characteristics and properties. The soluble salts are leached down to lower horizons and the Na^{+} is replaced by exchangeable H^{+} on the exchange complex. This fact is evident from the high exchange acidity values in the surface horizons as reported by Bowser et al. (1962) and Bentley and Rost (1947).

Data on the study of organic matter in Solonetzic soils are scanty. Some work has been done in Russia.

Aleksandrova (quoted by Joffe, 1949) reported that 59 to 64 per cent of the total organic matter in Solonchak is humin. The surface layer of Solonchak contains 15 to 16 per cent humic acid and 16 to 21 per cent fulvic acid. The lower part of the Solonchak profile contains very little organic matter.

As the Solonchak is desalinized, the Solonetz begins to lose organic matter. In a columnar Solonetz, there was 13.2 per cent of humic acid. An increase in fulvic acid also resulted from desalinization. The C:N ratio in the humic acid of Solonetz varies from 12 to 17. The exchange capacity of humic acid at pH 8.0 varies from 441 to 524 me./100 g. Novikova (1959) stated that the fulvic acids predominate over humic acids in the humus of Solonetz developed from tertiary clays. Somewhat similar results have been reported by Kaurichev and Panov (1957).

Mineralogical Characteristics of Solonetzic Soils

Numerous investigators (Mathieu, 1960; Whittig, 1959; Kellogg, 1941) reported montmorillonite is the dominant clay mineral in Solonetzic soils with minor amounts of illite and kaolinite. However, some workers (Grim, 1953; Kanwar, 1961) found illite as the principal clay mineral component in many Solonetzic soils. Vermiculite and chlorite, as constituents of the coarse clay fraction (2 to 0.2μ) have been reported in the A horizons of Solodized Solonetz soils of California (Whittig, 1959). Willing *et al.* (1963) in their study of primary minerals found that the parent material of Illinois Solonetz soils is rich in sodium feldspars.

From the results of various workers it may be concluded that the Solonetzic soils contain a wide variety of clay minerals. Clay minerals in these soils may be considered similar to those present in the surrounding zonal soil types.

Origin of Solonetzic Soils

The origin of Solonetzic soils has been explained by many investigators. Kovda (quoted by Muratova, 1958) in reviewing the results of various workers reported that the primary sources of salts of the earth's crust are the soluble products of volcanic eruptions, discharges of deep thermal energy sources, ancient salt-bearing deposits, and the products of mineralization of plant residue.

According to Glinka (1927) only those views which consider the combined influence of weathering processes and precipitation for the sources of the soil salts can be of significance. In isolated cases salts may be accumulated from each of the sources mentioned. However, if reference is made to salts which are distributed over wide areas in which neither marine deposits nor volcanic accumulations are present, their accumulation can be explained only through weathering and transportation by means of winds or precipitation. Precipitation may occasionally cause chlorides and sulphates as well as nitrates to accumulate in soils.

Kelley (1951) stated that Solonetzic soils have seldom been formed in place as a result of residual weathering of primary rocks. He believes that such soils usually have been formed from transported materials, much of which was extensively weathered. This is borne out by the fact that a high percentage of the alkali soils of the world are alluvial in origin.

The influence of the topographical position and geomorphological condition is considered rather more pronounced

in the formation of salted soils than in any other soil group. Muratova (1959) reported that the soluble salt accumulation in the parent material and ground water is explained by the combination of physical and geographical conditions: the levelness of the location, high temperature and evaporability, and absence of natural drainage and runoff.

Salt accumulation in soil is affected chiefly by the ground water. Muratova (1959) stated that the extent of ground water action on the soil depends on the depth of the water table. The strongest effect on salt accumulation in the upper soil horizons is exerted by the ground water when the water table reaches the critical depth.

Salted soils in Alberta are primarily formed on till which is dominantly of Bearpaw shale in origin (Byrne and Farvolden, 1959). Since much of the area has been subjected to post-glacial sorting, there are local areas of lacustrine and alluvial saline parent material. It is assumed that during the glacial period many kinds of bedrock materials were broken up, crushed, and partly sorted out by glacial action. In some cases the bedrock materials were comprised of large quantities of soluble salts laid in sedimentary beds during preglacial times. The glacial debris was deposited at various places. It is further assumed that some of the soluble salts were dissolved in the glacial waters and deposited with lacustrine sediments.

Evolution of Solonetzic Soils

According to Dokuchaiev (quoted by Joffe, 1949), "The soil is the result of the combined activity and reciprocal influence of parent material, plant and animal organisms, climate, age of the land, and topography." These were considered by Dokuchaiev to be soil formers. Parent material and topography are the soil formers that are most influential in the formation of Solonetzic soils.

The formation of Solonchak is usually associated with the introduction of salts by the mineralized ground waters and their accumulation in the superficial horizons of the soil as a result of the evaporation of ground water on their capillary ascent to the surface. The approach to the surface, of mineralized ground water, may occur either along the shores of seas and oceans, in river valleys and lake basins, or in continental regions without external drainage under dry climatic conditions with an excess of evaporation over precipitation (Vilenskii, 1957).

Tazabekov (1958) stated that the predominant soils of the coastal plain are bog where ground water keeps the profile constantly moist so that the soils become strongly salinized in summer. Antipov-karataev and Kizilova (1962) reported that the sulphate-chloride type of salinization in the Garmsar plain and Dasht-i-karvin desert in southern Iran is related to the mineralization of ground water, fed by salts contained in tertiary rocks composing the southern slopes of the Elburz range.

Kovda and Zakherina (1959) found that the sodium carbonate accumulation is most evident where plutonic waters with low salt content come close to the surface. The causes for the chloride-sulphate salinization in Sinkiang soils are the removal and accumulation of salts from the tertiary parent materials and the outcropping of deep oil-bearing rocks. Ballantyne (1963) postulated that salinization in soils of southeastern Saskatchewan has occurred as saline subsurface water moves latterly down the slope.

Polynov (quoted by Vilenskii, 1957) introduced the concept of the critical depth of ground water, that is, the maximum depth of the water table for which salinization of the surface horizon is possible. The critical depth for soils and sub-soils of various mechanical composition, as reported by Polynov, lies within the limits of 1.5 to 3.5 m.

Van Schaik and Milne (1963) found that considerable salinization occurred in a grass-covered soil in southern Alberta where the saline ground water was maintained at a depth of 3 feet. Gardner and Fireman (1958) indicated that salinization of surface soils occurred when the depth of water table was 60 to 90 centimeters from the surface. Asghar et al. (1952) in West Pakistan demonstrated that the rise of salts has been quite rapid even in those areas where the water table was more than 10 feet down from the soil surface.

Szabolcs and Miklay (1962) reported that the formation of the alkali soils in Gyor region of Hungary is mainly brought about by hydrological conditions. Of these, the greatest role

is played by the depth, fluctuation, and composition of the underground water.

According to Vilenskii (1957) and Rode (1962), the degree of salt accumulation for equal depth of ground water increases with the increase of their mineralization and is primarily associated with the aridity of the climate. When mineralization is small, bicarbonates and carbonates of alkalis predominate in the salt composition, which leads to the formation of soda solonchak.

Reactions of the soda forming processes in soil have been described by many workers. According to Hilgard (1918) the reaction is a reversible one, consisting of the reaction of the carbonates of lime and magnesia on the chlorides and sulphates of the alkalis (sodium) in the presence of an excess of carbon dioxide. This reaction takes place more readily if only sulphates are present since the gypsum that is formed is less soluble than calcium chloride. It crystalizes out of the solution and hence prevents any reverse reaction.

$$CaCO_3 \text{ (or } MgCO_3) + 2NaCl \rightleftharpoons CaCl_2 \text{ (or } MgCl_2) + Na_2CO_3$$

$$CaCO_3 + Na_2SO_4 \longrightarrow CaSO_4 + Na_2CO_3$$

According to Glinka (1927) the sodium carbonate forms mainly in deep horizons. If, however, the salt solutions rise toward the surface, a reverse reaction sets in and sodium sulphate and calcium carbonate are formed by a reaction with gypsum. Since this reaction acts slowly, it may take place in any horizon depending upon the rate of rise and evaporation of the solution. Glinka believed that in addition to temperature

and moisture, as described by American investigators, the composition and distribution of the salts are also influenced by capillarity, degree of solubility, and by the great variety of the crystal forms of the salts.

Rode (1962) stated that soda may form as a result of reduction of sulphates by sulphate-reducing bacteria in the presence of humus. He presented the corresponding reactions as follows (assuming the organic matter is cellulose):

$$3Na_2SO_4 + C_6H_{10}O_5 \longrightarrow 3Na_2S + 6CO_2 + 5H_2O$$

$$Na_2S + H_2CO_3 \longrightarrow H_2S + Na_2CO_3$$

or $$Na_2S + CaCO_3 \longrightarrow CaS + Na_2CO_3$$

Thus, according to Rode, soda formation requires the simultaneous presence of sulphates and of organic matter.

A new set of reactions are usually initiated as a result of desalinization of the solonchaks. Desalinization may result from improved drainage, by removing the source of surface and ground water, or by an increase in precipitation which involves a change in climate (U.S. Salinity Laboratory Staff, 1954). As a result of the removal of excess salts, the soil colloids become highly dispersed and the soil becomes alkaline in reaction. This alkalinity is attributed to the hydrolysis of the sodium from the exchange complex according to the following scheme:

$$Na\text{-Soil} + HOH \longrightarrow H\text{-Soil} + NaOH$$

$$2NaOH + CO_2 \longrightarrow Na_2CO_3 + H_2O$$

or $$Na\text{-Soil} + CaCO_3 \longrightarrow Na_2CO_3 + Ca\text{-Soil}$$

If the exchangeable sodium constitutes 10 to 15 per cent of the total exchangeable cations, there is an appreciable dispersion of the soil colloids. Joffe (1949) stated that with the same quantity of replaceable sodium, the Solonetz properties are more pronounced in the less arid regions than in more arid regions. The dessication effects in the arid regions mitigate considerably the dispersion of the colloids.

Rode (1962) stated that because of the strong dispersion of soil colloids, and also because of the strong alkalinity, such a soil is subjected to a peculiar soil forming process. A part of the peptized colloids, in the form of suspension and soil, is leached directly from the upper into the lower horizon. Another portion undergoes a preliminary chemical decomposition by the action of microorganisms, water, carbonic acids, and other agents. This is facilitated by the peptized state of colloids (because of their high active surfaces). The products from the decomposition of colloidal particles are likewise leached into the lower horizons. Humic compounds contribute to the dissolving of such products, either in proper or in colloidal solution. These compounds, being saturated with sodium, dissolve easily in water and form complex ions with mineral oxides especially those of iron and aluminum and retain them in solution. Laslo (1961) indicated that in soils undergoing solonization, the soluble iron content was larger in the top 20 cm. than in some or all of the lower horizons.

Rode (1962) stated that under alkali conditions soluble alkali silicates are formed and move down the profile.

At a certain depth they are coagulated by the strong electrolytes which have not yet been leached. The coagulation of these colloidal compounds forms a dense, compact, and intractible illuvial horizon which is commonly referred to as a solonetzic B horizon.

Some workers are of the opinion that the thickness of this compact B horizon depends upon the type of anion accompanying the sodium cation. Krupkin (1959) found that when the monoliths of leached Chernozems were treated with solutions of different sodium salts, the thickness of the solonized layer was greatest with sodium sulphate. He attributed this fact to the combination of displaced calcium with sulphate. McGeorge et al. (1926) stated that the precipitation of the soluble aluminates as colloidal aluminum hydroxides greatly reduces the permeability of the soil. The precipitation of aluminates occurs when the alkalinity of the soil is lowered either by leaching or by any other process.

Differences in opinions exist in the literature as to the formation of solonetzic B horizons. According to Gedroiz and de Sigmond (1925, 1938) the second stage (Solonetz) in the evolution of Solonetzic soils involves base exchange wherein the soil acquires a high amount of replaceable sodium. It has been pointed out by some workers (Kelley, 1934; Rost and Maehl, 1943) that by this standard many of the North American Solonetzic soils, described in the literature, are not true Solonetz. Bentley and Rost (1947) tabulated the data showing the proportions of exchangeable sodium, magnesium, and calcium in some Solonetzic

soils reported by various workers in North America. From the comparison of the data they concluded that magnesium is the dominant exchangeable cation in most of the Solonetzic profiles in the United States and Canada. These authors explained the high magnesium content in the horizon as a result of the precipitation of this element after it became mobile by the process of solodization. As quoted by these authors, Breazeale (1929) showed that when a calcareous soil, the pH of which is between 7 and 8, is leached with a mixture of calcium and magnesium salts, accumulation of magnesium carbonate results in the soil due to the following reaction:

$$CaCO_3 + Mg^{++} \longrightarrow MgCO_3 + Ca^{++}$$

The calcium carbonate would be constantly removed by the subsequent leaching of upper horizons with carbonated water leaving behind magnesium carbonate. Eventually, leaching would dissolve the magnesium and during the course of this leaching process the magnesium ions would displace the other adsorbed ions in the soil and thus dominate the exchange complex.

Uzakov (1961) stated that high exchangeable magnesium in the soils of the Zeravshan Valley is the result of a high rate of evaporation of bicarbonate ground waters. Magnesium carbonates may ascend through the capillaries to the very surface, in which case the magnesium cations would be more plentiful than calcium cations in soil solutions of upper horizons. Riecken (1943) believed that the high proportion of magnesium ions in many Solonetzic soils is due to the high rate of weathering of primary and secondary minerals which contain magnesium ions.

Another explanation for high exchangeable magnesium in Solonetzic soils can be deduced from Krupkin's (1959) experiments. If sulphates are the dominant anions in the soil, relatively insoluble gypsum ($CaSO_4$) would form and the entrance of calcium into the exchange complex would be reduced. Obviously, the adsorption of magnesium would be favoured in such cases.

However, the critical examination of the data on Mg-Solonetz soils appears to indicate that the lower horizons of most of the Solonetz soils do show a trend towards increased soluble sodium content. It is, therefore, possible that salts of monovalent sodium which have higher solubility than salts of divalent magnesium have been replaced by magnesium ions and added to the ground water. This question still remains to be fully resolved.

The next stage in the evolution of Solonetzic soils is the degradation of the exchange complex as a result of sustained leaching. Under the prevailing conditions, the hydrogen ions of the water gradually replace exchangeable sodium and form base-unsaturated particles. When the sodium ions are displaced from the exchange complex, the A horizon becomes more acidic and the reaction of the B horizon also becomes less alkaline (U.S. Soil Survey Staff, 1951). Rode (1962) stated that at this stage the concentration of sodium at the upper part of the B horizon is so low that it does not coagulate the moving colloids. Therefore, the destruction of colloids continues periodically and extends downwards through the illuvial B horizon. A similar view is presented by Nikiforoff and Drosdoff (1943) who supported the opinion that the A2 horizon results

from a subsequent degradation of the clay-pan caused by the change in the hydrologic regime of the soil. Joffe (1949) stated that at this stage of evolution (Sołodized Solonetz) the breakdown of silicates, referred to as solodization, begins resulting in a pronounced movement of colloids. As a result of this intense eluviation, there occurs a drastic change in the mineralogical characteristics of the A horizon. These characteristics may be easily noticed in the lower part of the A horizon (Ae or A2). This eluviated horizon is siliceous, light grey to ashy grey in colour, and very platy in structure.

With the complete breakdown of the structure and slaking of the colloids to their ultra-mechanical composition, some of the silicates become hydrolyzed to the point where amorphous silica separates (Joffe, 1949). Rode (1962) believed that this precipitation of amorphous silica may be a purely physico-chemical phenomenon. However, Tyurin, as quoted by Rode, reported that a considerable role is played by living organisms, particularly by microscopic diatoms. These organisms assimilate the silicic acid from solution and use it for building their frustules. After the death of diatoms, these frustules accumulate in the upper soil horizons. With the lapse of time, this amorphous silica crystalizes slowly and becomes, in part, a secondary quartz. The importance of biological processes has been recently shown by Kaurichev et al. (1959) who reported that these processes were much more intense in soils undergoing solodization.

Gedroiz, as quoted by Joffe (1949), differentiated between two types of solodization: (1) solodization of

carbonate-free Solonetz and (2) solodization of Solonetz containing carbonates. During the solodization of carbonate-free Solonetz, an intense decomposition of the alumino-silicate nucleus of the adsorption complex takes place. Gedroiz believed that the soil solution of the solodizing soil should be very rich, in comparison with the podzolized soils, in colloidal soluble silicic acids and sesquioxides. Because of their comparatively high concentration, these compounds should be in less stable condition than in the soil solution of podzolized soils. Their instability in solodized soil is further accentuated because of the presence of some soluble sodium salts in the Solonetz at the time this process begins, and because of the high content of soda in the soil solution in the latter stages of solodization. At this stage of development, the A horizon becomes quite thick and there is complete breakdown of the solonetzic B horizon. The reaction in the upper horizons (solum) is usually acidic.

Solodization is less vigorous in carbonate Solonetz as pointed out by Gedroiz. Calcium in the soil solution, under the prevailing conditions, gradually displaces the adsorbed sodium, thereby transforming the adsorption complex of the Solonetz from a state of partial or total sodium saturation to that of calcium saturation. In solodization of carbonate-Solonetz, the organic portion is comparatively less affected. Under these conditions it is obvious that after the solodization stage is completed in the Solonetz, the adsorption complex will not be completely destroyed since sod development can restore the organic portion of the adsorption complex which in this case will be saturated with exchangeable calcium ions.

Akhtyrtsev and Dzhegeris (1959) stated that the solods formed from crusty carbonate Solonetzes, in the southern Oka-Don lowlands, develop according to the following sequence: Solod — grey Solodized soil -- dark grey Solodized soil. These authors suggested that the evolution of the solods in this direction is closely connected with the invasion of broad leaf trees into the aspen scrub, their thinning, and the development of grass in the scrub. Increased local drainage and a lower water table also play an important role in the evolution of the Solods in this particular area.

Stability of Clay Minerals

A knowledge of the stability of clay minerals to weathering is essential for a proper understanding of the intensity of the pedogenic processes. Weathering of the clay minerals, in the evolution of Solonetzic soils, may be considered to represent the extent to which solodization has proceeded. As indicated in the previous section, with the onset of solodization in carbonate-free Solonetz, degradation of alumino-silicates takes place which essentially reflects the intensity of various soil forming processes.

Various minerals in the clay-size fraction of soils were determined by Jackson et al. (1948, 1952) and arranged into a weathering sequence. According to the weathering sequence (a list of minerals according to their relative stability to weathering) established by Jackson et al. (1948), clay minerals that commonly occur in soils may be arranged as follows:

kaolinite > montmorillonite > vermiculite > illite.

Jackson et al. (1948) stated that, in general, increasing acidity and increasing oxidation favour increased weathering intensity. Thus, prolonged leaching under reducing conditions would not lead through the above weathering sequence. For example, weathering of montmorillonite to kaolinite will not result while leaching is lacking. This fact may also be observed in the development of Solonetzic soils. Improved drainage is essential in order for the Solonchak - Solonetz - Solodized Solonetz - Solod sequence to develop.

The effect of proton intensity (pH) on the stability of the clays is a subject of wide discussions among many soil scientists. Very recently Jenny (1961) presented an excellent review on this subject. His main attempt, in this review, was to develop the concept that the clays under acidic environment exist as H-Al-clays rather than simply H-clays. Many investigators (Russell, 1961; Harward and Coleman, 1954) demonstrated that if the clays are saturated with H^+ a transformation to H-Al-clays will occur with a lapse of time. The Al ions released from the clay play a major role in developing the soil acidity (Harward and Coleman, 1954; Heddleson et al., 1960).

Chernov (1959) reported that the H^+ occupying the exchange sites of the clays are fairly mobile and hence enter into a chemical reaction with the non-exchangeable basic forms of Al^{+++} and Mg^{++} forming part of the structure of the crystal lattice of montmorillonite.

Barshad (1960) reported that the Mg^{++} ions contribute a substantial percentage of the total exchangeable cations in acidified clay samples from various soil profiles. He believed

that the high quantity of exchangeable Mg^{++} commonly found in Solonetzic soils is due to the fact that under alkaline conditions the exchangeable H^{+} gained by the soil through hydrolysis tends to be replaced by Mg^{++} rather than Al^{+++} (from octahedral layers). He further postulated that the adsorbed H^{+} on the mineral surfaces readily enters the interior of the crystal lattice to displace Al^{+++}, Mg^{++}, and possibly Fe^{++} or Fe^{+++} wherever these are present. By this mechanism, the chemical alteration and breakdown of the silicate mineral goes through the first stage of weathering. Similar results were reported by Kerr et al. (1955) in their study on the degradation of hectorite under an acidic environment.

Some workers (Jackson and Sherman, 1953) stated that the formation of montmorillonite is favoured under alkaline conditions while kaolinite forms in an acidic environment.

Traces of strong acids such as HNO_3 and H_2SO_4 may form on decomposition of organic matter and minerals and aid in Al^{+++} release (Jackson, 1963). However, it has been shown that H_2CO_3 present in soil solution aids in the decomposition of both montmorillonite (Corren, 1961) and kaolinite (Polzer, 1961). The alumina released from such decomposition processes forms an interlayer phase between the expansible layer silicates. Shen and Rich (1962) attributed the low C.E.C. of montmorillonite to the formation of hydroxi-aluminum interlayers at low pH values. The hydroxi-aluminum groups in acid soils may result in the formation of kaolinite (Jackson, 1960) and gibbsite (Barnhisel and Rich, 1963). Some workers (Jackson, 1963) stated that old, well weathered soils tend to have clay minerals in the fraction

greater than 0.2 microns. In such cases the attack by H_3^+O (acid ion in solution) and release of alumino-hydronium at layer edges destroys the smaller montmorillonite layers rather completely.

Barshad (1958) stated that the relative stability of the minerals to weathering and to decomposition with acid appears to be related to the degree of basicity, degree of linkage of the tetrahedrons, relative number of alumina and silica tetrahedrons, and other factors that induce a lowering of the basicity of the mineral and a destruction of bonds linking the tetrahedrons. Kimpe et al. (1961) reported that the main factors contributing to the synthesis of aluminum and magnesium silicates are: pH, salt concentration, and the ratio of aluminum or magnesium content to the silica content.

Pawluk (1960), who identified chlorite-like minerals in B horizons of Podzols, suggested that its occurrence is partly the result of major changes in the crystal lattices of illite and montmorillonite. Some workers believed that the chlorite and illite change to montmorillonite following the oxidation of Fe^{++} in the octahedral layers (Murray and Leininger, 1955). Jackson et al. (1952) suggested that the alteration of mica to montmorillonite is the result of depotassication of the mica minerals. Similarly, kaolinite may be formed as a result of desilication of the 2:1 layer mineral.

The mechanism involved in the genesis of clay minerals are greatly influenced by the proton intensity in the soil solution. However, some workers believe that pH may not be solely responsible for the formation of the clay minerals found

in soils. Pawluk (1961) studying the Grey Wooded soils concluded that the most severe weathering need not necessarily occur in the most acidic horizons. He further suggested that minerals are much more stable under acid conditions resulting from the presence of exchangeable Al^{+++} than where H^{+} contributes to the exchange acidity.

The nature of the interlayer cation also plays a measureable role in the stability of clay minerals. Mumpton and Rustum (1955) studied clay mineral stabilities under high water pressures and elevated temperatures and concluded the following ascending order of stability for four cations: Na^{+}, Mg^{++}, Pb^{++}, Ca^{++}. From the results obtained by these workers, it appears that the stability of clay minerals in Solonetzic soils would be low because they are primarily saturated with Na^{+} and Mg^{++} cations.

Another factor that plays a significant role in a weathering sequence is the oxidation of Fe^{++} to Fe^{+++}. Murray and Leininger (1955) reported that the transformation of chlorite and illite to montmorillonite seems to result from the oxidation of the iron in the lattice and subsequent leaching of Mg^{++} and K^{+}.

Eluviation and illuviation are the two most important processes that lead to the development of the soil profile. These processes primarily result from the microbiological activities, water movement, and dispersion and flocculation. Ehrlich and Smith (1958) reported that the illuvial clay is more pronounced in the B horizons of Solodized Solonetz than the B horizons of Solonetz soils. Mathieu (1960) demonstrated the

movement of undecomposed clay from the A2 horizon to the B1 horizon of Solodized Solonetz soils. Antipov-karataev (1960) suggested that a specific solonetzic horizon may be formed by the infiltration of unchanged and finely dispersed soil material at or near neutral reactions or by a hydrolytic process involving migration of silicates and sodium aluminates at strong alkaline reaction in solodized soils.

Thorp et al. (1957) reported that organic acids and water soluble materials found in leaves play a significant role in the profile development. In their leaching experiment they observed that a detectable amount of fine silicate clays move in suspension, with appreciable quantities of calcium, magnesium, iron, and manganese. Barshad (1958) stated that particles 0.1 micron or less in diameter, consisting of minerals of the montmorin type and mixed with uncombined iron and aluminum oxides, move down the profile. He further postulated that with increasing clay content, through migration (and formation), the depth to which clay can move decreases gradually until movement may completely cease as it probably does in some soils which have dense clay pans.

MATERIALS AND METHODS

Description of the Sampling Area

The Solonetzic soils, sampled for this study, occur in the glacial Lake Edmonton basin and are associated with Black Chernozemic soils. These soils are usually found on level to depressional topography and are developed from saline lacustrine clay parent geologic material.

The climate of the sampling area is continental characterized by relatively warm summers and cold winters. The mean annual precipitation is from 16 to 18 inches and the climate is considered to be between dry and moist sub-humid. June, July, and August are the months of highest rainfall which is of the low intensity variety, totalling an average of about 9 inches. Approximately 70 per cent of the precipitation falls as rain and the remainder as snow. The average annual snowfall is just over 50 inches, varying from 10 to 90 inches. The mean annual temperature is 37°F., July being the warmest month averaging 61.5°F. The average wind velocity in this area is just under 10 miles per hour with little variation throughout the year (Bowser et al., 1962).

The area of sampling has lacustrine parent material, underlain by Upper Cretaceous bedrock. The main rock formations in this area, as described by Bowser et al. (1962), are Edmonton and Bearpaw shale. The parent materials contain varying amounts of salts and/or lime.

The vegetation is mainly composed of tall coarse grasses, shrubs, and in some cases trees. The vegetation

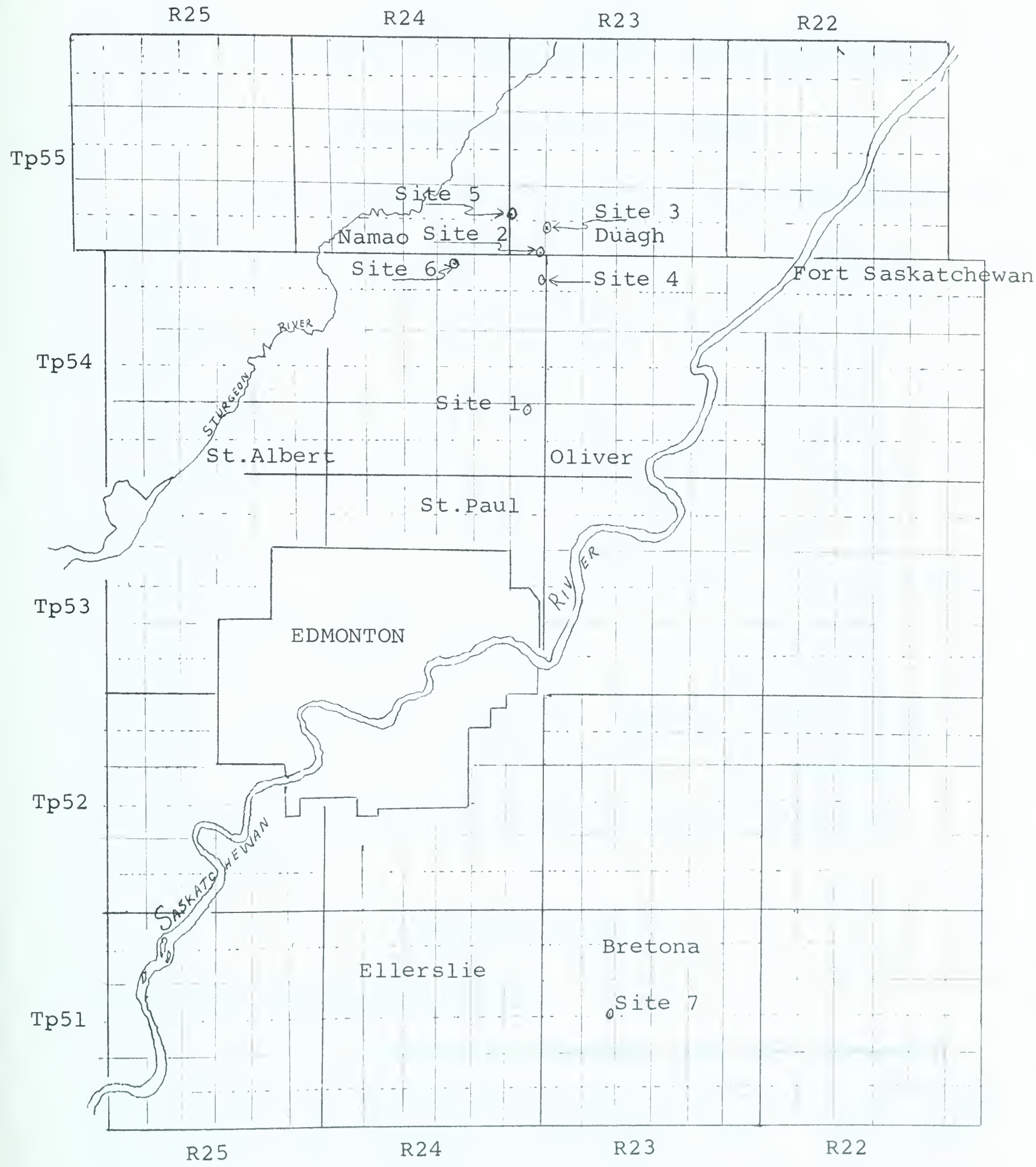

Figure 1. Map of the sampling area.

frequently noticed includes:

1. Common wild rose (Rosa woodsii Lindl.)
2. Dogwood (Cornus stolonifera Mich.)
3. Snowberry (Symphoricarpos occidentalis Hook.)

Description of the Soil Samples

Seven different soil profiles in the above mentioned area were exposed and samples were collected on a horizon basis. The detailed descriptions of each profile are given in Tables II to VIII. The descriptions are based on the features apparent on the exposed profile and on observations made while digging the pit. The soils under study were classified on the basis of both morphological and chemical characteristics of the respective profile horizons. The designations of soil horizons is in accordance with the nomenclature adopted by the National Soil Survey Committee of Canada (1963). Colour description is given according to the Munsell system of colour notation. Textural classes, based on data obtained from mechanical analyses, were determined by means of a textural classification diagram devised by Toogood (1958).

Laboratory Methods

Preparation of the Soil Samples

The soil samples were brought into the laboratory, air dried at room temperature and ground with a porcelain mortar and pestle to pass through a 2 millimeter sieve. The prepared samples were stored in glass screw-top containers until needed for analyses.

TABLE II. Profile Description of Site 1. (Black Solodized Solonetz)

Legal Location: NW 12 - 54 - 24 W4

Horizon	Depth (in.)	Colour* Dry	Colour* Moist	Texture	Structure and Consistency
Ah1	0- 3	Very dark grey 10 YR 3/1	Black 10 YR 2/1	SiCL	Fine granular, friable
Ah2	3- 7	Very dark brown 10 YR 2/2	Black 10 YR 2/1	SiCL	Granular, friable
Ahe	7- 8	Very dark greyish brown 10 YR 3/2	Very dark grey 10 YR 3/1	SiCL	Crumby with remnants of tops of old columns, friable
AB	8- 9	Dark grey 10 YR 4/1	Very dark greyish brown 10 YR 3/1	CL	Columnar breaking readily to medium to fine blocky structure, firm
Bnt1	9-11	Dark greyish brown 10 YR 4/2	Very dark greyish brown 10 YR 3/2	SiCL	Coarse blocky, very firm
Bnt2	11-16	Dark greyish brown 10 YR 4/2	Very dark greyish brown 10 YR 3/2	SiC	Coarse to medium blocky with dark coatings of organic matter, very firm
Bnt3	16-20	Greyish brown 10 YR 5/2	Very dark greyish brown 10 YR 3/2	C	Medium blocky, very firm
Bs	20-28	Greyish brown 10 YR 5/2	Dark greyish brown 10 YR 4/2	C	Fine to medium blocky, firm
Cca	28-36	Light brownish grey 10 YR 6/2	Dark greyish brown 2.5 Y 4/2	HC	Fine irregular blocky, firm with uniform distribution of salts
C	36-42	Greyish brown	Olive brown 2.5 Y 4/4	SiC	Fine blocky to massive, firm. Evidence of salt varving
Cs	42-55	Light brownish grey 2.5 Y 6/2	Olive brown 2.5 Y 4/4	SiC	Massive with small pockets of salts, firm
II C1	55-72	Light yellowish brown 2.5 Y 6/4	Light olive brown 2.5 Y 5/4	CL	Massive, plastic, slightly sticky
II C2	72-76	Light yellowish brown 2.5 Y 6/4	Light olive brown 2.5 Y 5/4	SiCL	Massive, plastic

* Munsell colours

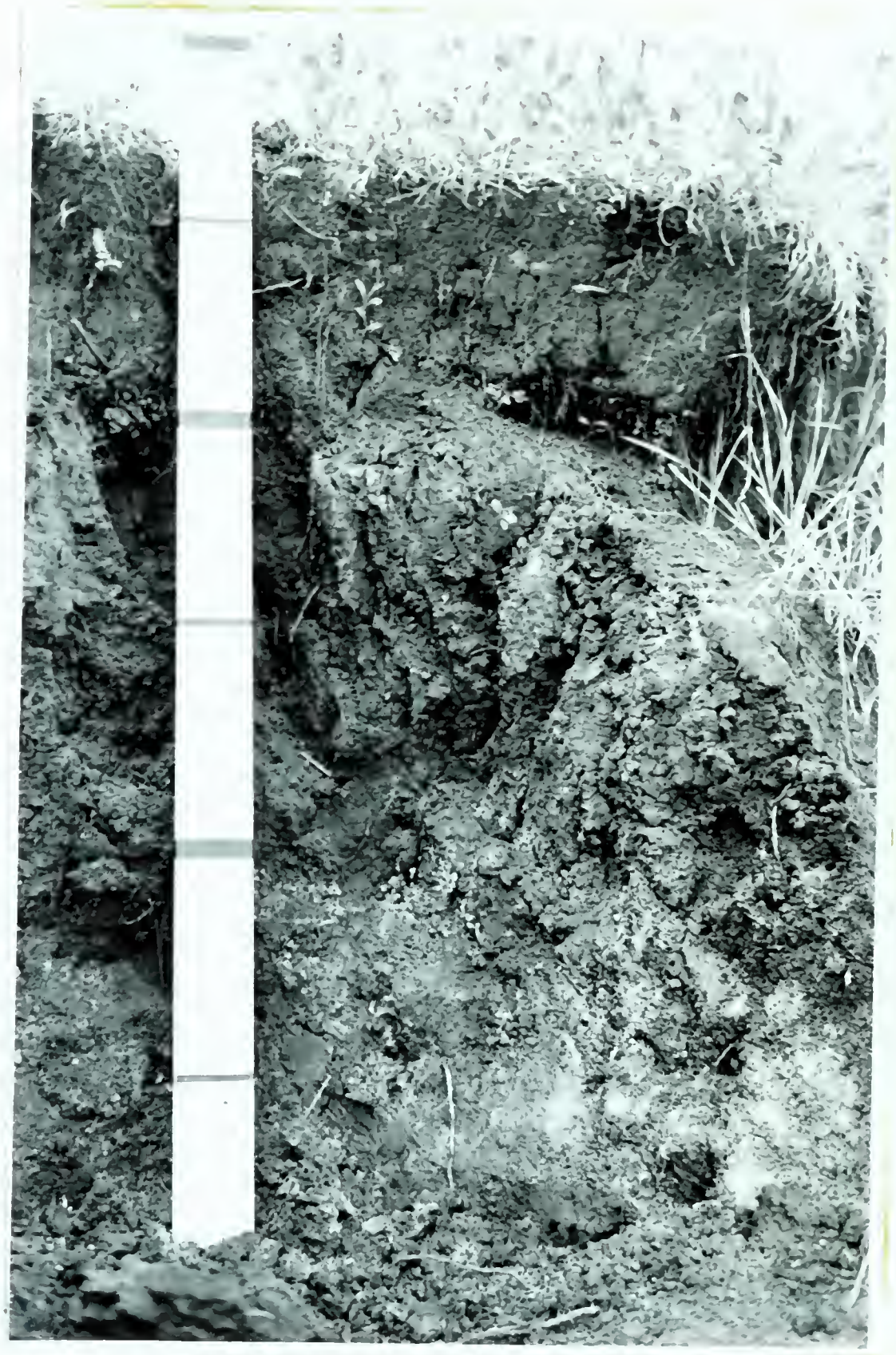

PLATE 1. Morphological Characteristics of Soil Profile at Site 1.

TABLE III. Profile Description of Site 2. (Black Solonetz)

Legal Location: SE 6 - 55 - 23 W4

Horizon	Depth (in.)	Colour* Dry	Colour* Moist	Texture	Structure and Consistency
Ah	0- 3	Very dark grey 10 YR 3/1	Very dark grey 10 YR 3/1	SiC	Fine granular, very friable
Ahe	3- 4	Very dark greyish brown 10 YR 3/2	Very dark brown 10 YR 2/2	SiC	Fine granular, friable
Surface** of Bntl	4-10	Dark greyish brown 10 YR 4/2	Very dark greyish brown 10 YR 3/2	SiC	
Bntl	4-10	Dark greyish brown 10 YR 4/2	Very dark greyish brown 10 YR 3/2	HC	Round topped columnar, breaks with difficulty into a coarse blocky to massive meso-structure, extremely firm
Bnt2	10-16	Dark brown 10 YR 3/3	Very dark brown 10 YR 2/2	HC	Irregular blocky to massive, extremely firm
Bnt3	16-24	Dark greyish brown 10 YR 4/2	Very dark greyish brown 10 YR 3/2	HC	Medium blocky to massive, very firm
Bs	24-30	Light brownish grey 10 YR 6/2	Dark greyish brown 10 YR 4/2	HC	Massive, firm
Bsk	30-55	Light brownish grey 2.5 Y 6/2	Dark greyish brown 2.5 Y 4/2	HC	Massive, firm
Cs	55-65	Light yellowish brown 2.5 Y 6/4	Dark greyish brown 2.5 Y 4/2	HC	Massive with occasional pockets of salts, firm
C1	65-72	Light brownish grey 2.5 Y 6/2	Dark greyish brown 2.5 Y 4/2	HC	Massive, slightly plastic
C2	72-75	Light olive brown 2.5 Y 5/4	Olive brown 2.5 Y 4/4	SiCL	Massive, slightly sticky, and slightly plastic

* Munsell colours

** Material obtained by removing the surfaces of the columns of Bntl horizon. This shall apply throughout.

PLATE 2. Morphological Characteristics of Soil Profile at Site 2.

TABLE IV. Profile Description of Site 3 (Black Solonetz)

Legal Location: NW 5 - 55 - 23 W4

Horizon	Depth (in.)	Colour* Dry	Colour* Moist	Texture	Structure and Consistency
Ah	0- 3	Very dark grey 10 YR 3/1	Very dark grey 10 YR 3/1	SiCL	Fine granular, very friable
Surface of Bnt1	3- 9	Very dark greyish brown 10 YR 3/2	Very dark brown 10 YR 2/2	SiC	
Bnt1	3- 9	Very dark greyish brown 10 YR 3/2	Very dark brown 10 YR 2/2	SiC	Round topped columns, breaking with difficulty to massive meso-structure, extremely firm
Bnt2	9-11	Very dark greyish brown 10 YR 3/2	Very dark brown 10 YR 2/2	SiC	Irregular columnar breaking to massive meso-structure,extremely firm
Bs	11-16	Greyish brown 10 YR 5/2	Very dark greyish brown 10 YR 3/2	HC	Irregular blocky to massive with high concentration of salts, sticky to plastic
Cs	16-31	Greyish brown 10 YR 5/2	Dark greyish brown 10 YR 4/2	HC	Massive to blocky with salts occurring as rossettes,sticky,very plastic
Csk	31-45	Greyish brown 2.5 Y 5/2	Very dark greyish brown 2.5 Y 3/2	SiC	Fragmental, sticky and plastic
C1	45-55	Light brownish grey 2.5 Y 6/2	Dark greyish brown 2.5 Y 4/2	SiC	Fragmental to massive with pockets of lime and salts, sticky and plastic
C2	55-72	Light brownish grey 2.5 Y 6/2	Dark greyish brown 2.5 Y 4/2	SiC	Massive with occasional pockets of salts, sticky and plastic
C3	72-75	Light brownish grey 2.5 Y 6/2	Dark greyish brown 2.5 Y 4/2	SiC	Fragmental to massive, sticky and plastic

* Munsell colours

PLATE 3. Morphological Characteristics of Soil Profile at Site 3.

TABLE V. Profile Description of Site 4 (Black Solodized Solonetz)

Legal Location: NE 36 - 54 - 24 W4

Horizon	Depth (in.)	Colour* Dry	Colour* Moist	Texture	Structure and Consistency
Ah	0- 2½	Very dark grey 10 YR 3/1	Very dark grey 10 YR 3/1	SiCL	Fine granular, friable
Ahe	2½-4	Very dark brown 10 YR 2/2	Very dark grey 10 YR 3/1	SiCL	Weakly platy to fine granular, friable
Ae	4- 5½	Dark brown 10 YR 3/3	Very dark brown 10 YR 2/2	SiCL	Platy to granular, friable
AB	5½-6	Dark grey 10 YR 4/1	Very dark brown 10 YR 2/2	SiCL	Platy to blocky, friable to firm
Surface of Bnt1	6-10	Dark greyish brown 10 YR 4/2	Very dark greyish brown 10 YR 3/2	SiCL	
Bnt1	6-10	Dark greyish brown 10 YR 4/2	Very dark greyish brown 10 YR 3/2	SiC	Round topped columnar, breaks with moderate resistance to small blocky meso-structure, very firm
Bnt2	10-13	Dark greyish brown 10 YR 4/2	Very dark greyish brown 10 YR 3/2	SiC	Columnar breaking to small blocky meso-structure, very firm
Bnt3	13-18	Dark greyish brown 10 YR 4/2	Very dark greyish brown 10 YR 3/2	SiC	Medium blocky, very firm
BC	18-24	Dark grey 10 YR 4/1	Very dark grey 10 YR 3/1	SiC	Massive to blocky, very firm
Cs	24-31	Greyish brown 2.5 Y 5/2	Very dark greyish brown 2.5 Y 3/2	C	Massive, firm
Csk	31-40	Light brownish grey 2.5 Y 6/2	Dark greyish brown 2.5 Y 1/2	SiC	Massive with varving of salts, slightly sticky
C1	40-48	Light brownish grey 2.5 Y 6/2	Dark greyish brown 2.5 Y 4/2	SiC	Massive, slightly sticky
C2	48-72	Light brownish grey 2.5 Y 6/2	Dark greyish brown 2.5 Y 4/2	SiC	Massive, slightly sticky and plastic
C3	72-	Light brownish grey 2.5 Y 6/2	Dark greyish brown 2.5 Y 4/2	SiL	Massive, slightly sticky and plastic

* Munsell colours

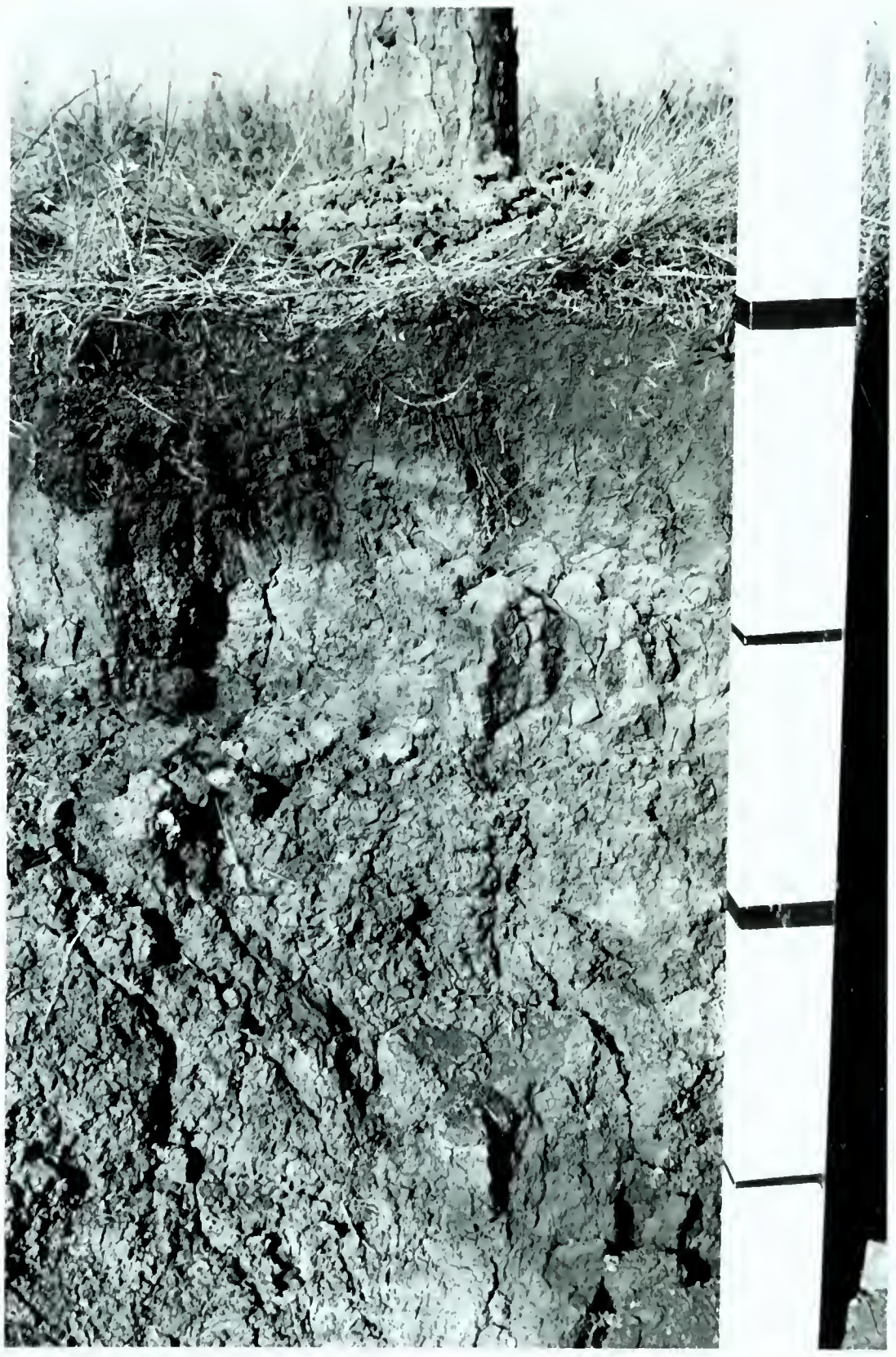

PLATE 4. Morphological Characteristics of Soil Profile at Site 4.

TABLE VI. Profile Description of Site 5 (Eluviated Black)

Legal Location: SW 7 - 55 - 23 W4

Horizon	Depth (in.)	Colour* Dry	Colour* Moist	Texture	Structure and Consistency
Ah1	0- 2	Very dark grey 10 YR 3/1	Very dark grey 10 YR 3/1	SiC	Granular, friable
Ah2	2- 8	Very dark brown 10 YR 2/2	Very dark grey 10 YR 3/1	SiC	Weak prismatic to weak irregular blocky,friable
Ah3	8-11	Very dark greyish brown 10 YR 3/2	Very dark grey 10 YR 3/1	SiCL	Small blocky, friable
Ahe	11-15	Dark grey 10 YR 4/1	Very dark grey 10 YR 3/1	SiCL	Weak platy to granular, friable
AB	15-15½	Dark greyish brown 10 YR 4/2	Very dark greyish brown 10 YR 3/2	SiC	Massive to irregular blocky, firm
Upper Bt1	15½-17	Grey 10 YR 5/1	Very dark greyish brown 10 YR 3/2	SiC	Weak columnar to weak subangular blocky, extremely firm
Lower Bt1	17-22	Greyish brown 10 YR 5/2	Very dark greyish brown 10 YR 3/2	C	Weak columnar to weak sub-angular blocky,very firm
Bt2	22-29	Greyish brown 10 YR 5/2	Very dark greyish brown 10 YR 3/2	C	Subangular blocky, very firm
Bt3	29-36	Greyish brown 2.5 Y 5/2	Dark greyish brown 2.5 Y 4/2	SiC	Weak prismatic to blocky, very firm
BC	36-46	Light brownish grey 2.5 Y 6/2	Dark greyish brown 2.5 Y 4/2	SiC	Blocky to massive, very firm
C1	46-52	Light olive brown 2.5 Y 5/4	Olive brown 2.5 Y 4/4	SiC	Massive, friable
C2	52-72	Light olive brown 2.5 Y 5/4	Olive brown 2.5 Y 4/4	SiCL	Massive, slightly sticky
C3	72-	Light olive brown 2.5 Y 5/4	Olive brown 2.5 Y 4/4	SiCL	Massive, slightly sticky

* Munsell colours

PLATE 5. Morphological Characteristics of Soil Profile at Site 5.

TABLE VII. Profile Description of Site 6 (Orthic Black (Solodic))

Legal Location: NE 34 - 54 - 24 W4

Horizon	Depth (in.)	Colour* Dry	Colour* Moist	Texture	Structure and Consistency
Ah	0- 4	Very dark grey 10 YR 3/1	Black 10 YR 2/1	SiC	Granular, friable
AB	4- 9	Very dark brown 10 YR 2/2	Very dark grey 10 YR 3/1	C	Weak prismatic, breaking to granular,friable to firm
Bm1	9-13	Very dark greyish brown 10 YR 3/2	Very dark brown 10 YR 2/2	SiC	Medium blocky, very firm
Bm2	13-18	Grey 10 YR 5/1	Very dark greyish brown 10 YR 3/2	C	Medium blocky to fine blocky, very firm
Cca	18-28	Greyish brown 10 YR 5/2	Dark greyish brown 10 YR 4/2	HC	Weak prismatic to fine blocky, firm
Ck	28-41	Greyish brown 10 YR 5/2	Dark greyish brown 10 YR 4/2	C	Fine blocky, with a layer of salt beds, firm
C1	41-52	Light brownish grey 2.5 Y 6/2	Dark greyish brown 2.5 Y 4/2	HC	Medium blocky, with a layer of salts, firm
C2	52-66	Light yellowish brown 2.5 Y 6/4	Olive brown 2.5 Y 4/4	SiCL	Massive, high in salts, slightly sticky
C3	66-68	Light yellowish brown 2.5 Y 6/4	Olive brown 2.5 Y 4/4	SiCL	Massive, sticky

* Munsell colours

PLATE 6. Morphological Characteristics of Soil Profile at Site 6.

TABLE VIII. Profile Description of Site 7 (Eluviated Black)

Legal Location: SE 20 - 51 - 23 W4

Horizon	Depth (in.)	Colour* Dry	Colour* Moist	Texture	Structure and Consistency
Ah	0- 4	Very dark grey 10 YR 3/1	Very dark grey 10 YR 3/1	SiL	Granular, friable
Ae	4-10	Grey 10 YR 6/1	Grey 10 YR 5/1	SiL	Platy, friable to firm
Upper Bt1	10-12½	Dark greyish brown 10 YR 4/2	Very dark greyish brown 10 YR 3/2	SiC	Round topped columnar, breaks to firm blocky structure, very firm
Lower Bt1	12½-15	Greyish brown 10 YR 5/2	Dark greyish brown 10 YR 4/2	HC	Columnar breaks to small blocky meso-structure, very firm
Bt2	15-21	Greyish brown 10 YR 5/2	Dark greyish brown 10 YR 4/2	HC	Massive, breaks to blocky, very firm
Bt3	21-26	Greyish brown 2.5 Y 5/2	Dark greyish brown 2.5 Y 4/2	SiC	Coarse blocky, very firm
BC	26-36	Greyish brown 2.5 Y 5/2	Dark greyish brown 2.5 Y 4/2	SiC	Weak blocky to massive, firm
Cs	36-44	Light greyish brown 2.5 Y 6/2	Dark greyish brown 2.5 Y 4/2	SiC	Massive, firm
Csk	44-60	Light greyish brown 2.5 Y 6/2	Dark greyish brown 2.5 Y 4/2	SiC	Massive, slightly sticky

* Munsell colours

PLATE 7. Morphological Characteristics of Soil Profile at Site 7.

Physical Analyses

Mechanical Analysis: The mechanical analysis was carried out by the pipette method described by Toogood and Peters (1953). The samples having high electrical conductivity values were dispersed in water and passed through ceramic filter cones to remove the soluble salts. During filtration the samples were washed with normal ammonium chloride to facilitate the removal of gypsum. The total sand fraction was separated by wet sieving and was further sub-fractioned by dry sieving. The fine clay was separated by centrifuging the clay suspension (Baver, 1959). The silt was calculated by difference.

The percentages for different fractions are based on oven dry weight of organic matter and carbonate free soil material.

Bulk Density: Bulk density was determined on core samples collected with a "Bull Core Sampler". The samples were oven dried, weighed, and the bulk density calculated.

Colloid Movability: The colloid movability was determined by the procedure used by Blümel et al. (1960) with some modifications. Since the method is relatively new and has not been widely used, a detailed description was felt warranted.

1. Place one gram of soil in a centrifuge tube.
2. Add 20 ml. of CO_2-free water to the soil in the centrifuge tube.
3. Shake for one hour.
4. Centrifuge so that only fine clay ($< 0.2\,\mu$) remains in suspension.

5. Place 10 ml. of this suspension in a coagulation tube and flocculate with 0.5 ml. of 20 per cent $Ca(NO_3)_2$ solution.
6. Shake the contents in the coagulation tube vigorously for 5 minutes. Allow to stand for 24 hours and measure the volume of the coagulate. This is fraction WI.
7. Obtain fraction WII by mixing the sediment from step 4 in the centrifuge tube with 15 ml. of CO_2-free water and repeating steps 3 to 6. The volume of coagulate obtained is fraction WII.
8. Repeat step 7 once again to get fraction WIII.
9. Repeat the whole procedure with 0.2 per cent $LiCO_3$ solution instead of CO_2-free water to give LiI, LiII, and LiIII values.

Calculations: $$\text{Coagulation factor} = K = \frac{LiI}{WI}$$

$$\text{Stability factor} = St = \frac{LiII + LiIII}{WII + WIII}$$

$$\text{Colloid movability} = \frac{1}{K + St}$$

The coagulation and stability factors are related to the dispersion of clay colloids by the lithium solution while the colloid movability provides a measure of the movement of the finest particles in the soil profile.

Chemical Analyses

Soil Reaction: The pH of a saturated paste was measured with a Beckman Model H-2 pH Meter equipped with glass and calomel electrode.

Electrical Conductivity of Saturation Extracts: A saturation paste was prepared according to the procedure outlined by the U.S. Salinity Laboratory Staff (1954). The saturation extract was obtained by centrifugation and the conductivity of the extract was measured with a direct reading Solu-Bridge Model RD-26.

Soluble Salts: The soluble cations measured in the saturation extract were Na^{+}, Ca^{++}, and Mg^{++}. The Na^{+} was determined with a Beckman Model DU flame spectrophotometer at 589 mμ. The Ca^{++} and Mg^{++} were determined by complexiметric titrations with EDTA as outlined by Cheng and Bray (1951).

Carbonates and bicarbonates in the saturation extracts were determined with the use of a radiometer titrator type TTT1b equipped with a glass electrode and mercuric chloride calomel half cell. The solution was titrated with 0.001 N H_2SO_4 to pH 8.0 for CO_3^{--} and pH 4.4 for HCO_3^{-}. The CO_3^{--} was considered to be absent, if the pH of the solution was less than 8.0.

Chlorides were measured with the above radiometer titrator but in this case a silver electrode and a mercuric sulphate calomel were used to determine the end point. The solution was titrated with 0.001 N $AgNO_3$ solution until the potential of the solution was equal to a blank. Prior to titration, 25 ml. of 50 per cent acetic acid was added to each sample solution in order to facilitate the coagulation of fine particles in the precipitate. To ensure the complete recovery of Cl^{-} from the samples, standard Cl^{-} solutions, containing 0.5 gram each of Na_2CO_3, $NaHCO_3$, $MgSO_4$, K_2SO_4, and $CaSO_4$, were

titrated. The method was found to be accurate within 0.5 per cent for the Cl^- values tested.

Sulphates were determined by the turbidimetric method. A Coleman spectrophotometer was used for the determination at a wavelength of 425 mμ.

Exchangeable Cations: The exchangeable cations were calculated as the difference between the extractable cations and soluble cations. The soluble cations in the surface horizons having pH values less than 7.0 were found to be negligible. The exchangeable cations were extracted from the soil samples with 1 N $NH_4C_2H_3O_2$ solution adjusted to pH 7.0 as outlined in the A.O.A.C. methods of analysis (1955).

The exchangeable Na^+, K^+, Ca^{++}, and Mg^{++} were determined with a Beckman Model DU flame spectrophotometer. The Na^+ was measured at 589 mμ, K^+ at 769 mμ, Ca^{++} at 422 mμ, and Mg^{++} at 285 mμ.

The exchange acidity values were determined on the extract obtained by leaching the soil with 0.5 N $Ba(C_2H_3O_2)_2$ adjusted to pH 7.0 and titrating the extract with standardized NaOH solution (Brown, 1943). A mixture of triethanolamine and $BaCl_2$ (pH 8.1) was also used as an extracting solution where the exchange acidity was determined by titrating the extract with standardized HCl (Mehlich, 1948).

Exchangeable Aluminum: The exchangeable Al^{+++} was extracted with 1 N $NH_4C_2H_3O_2$ (pH 4.8) as outlined by Mclean et al. (1958). Colorimetric determinations of exchangeable Al^{+++} was conducted with the aid of a Beckman Model DU spectrophotometer at 520 mμ according to the procedure outlined by Robertson (1950).

Cation Exchange Capacity: The cation exchange capacity was determined by the method outlined by the A.O.A.C. (1955) with some modifications suggested by Pawluk (1955).

Calcium Carbonate Equivalent: A modification of the procedure described in the A.O.A.C. methods of analysis (1955) was used for $CaCO_3$ determination. The CO_2 evolved by treating the soil samples with H_2SO_4 and $FeSO_4$, was absorbed in a Nesbitt tube. The $CaCO_3$ equivalent was calculated from the weight of CO_2 evolved.

Organic Carbon: Organic carbon content was determined by the dry combustion method, as outlined in the A.O.A.C. manual (1955).

Total Nitrogen: Total nitrogen was determined by the Kjeldahl-Wilfrath-Gunning method (1955). The catalyst used was K_2SO_4 - $CuSO_4$ - Se mixture in proportions of 1,000 : 25 : 10 by weight. Distilled ammonia was collected in 4 per cent boric acid solution as suggested by Meeker and Wagner (1933) and titrated against standard H_2SO_4 using a mixed indicator (methyl red-bromcresol green).

Soluble Aluminum and Silica: For the determination of soluble aluminum and silica, 1 g. of soil sample was placed in 100 ml. of 5 per cent Na_2CO_3 solution and heated to boiling. The sample was then filtered and the filtrate collected in poly-ethylene beakers. The organic matter was destroyed with 10 per cent H_2O_2 and the excess H_2O_2 boiled off in glass beakers. Prior to heat treatment it is essential to acidify the filtrate, as the alkaline solution will solublize the silica from the glass beakers used in this step. Care was taken to avoid the

contamination of silica from the glass ware used during the extraction.

The silica was determined colorimetrically with a Beckman Model DU Spectrophotometer at 400 mμ as outlined by Corey and Jackson (1953). Soluble aluminum was also determined colorimetrically as mentioned previously.

Free Iron Oxide: Mackenzie's (1954) method was used to determine free Fe_2O_3, with some modifications. Dry $Na_2S_2O_4$ was added to the suspension of soil and water instead of adding the salt as a solution to the wetted soil. The modification prevents the autodecomposition of the salt prior to its addition to the soil. Iron was measured colorimetrically at 500 mμ using O-phenanthroline for colour development.

Mineralogical Analyses

Preparation of Clay Samples: Particle size segregation of soil samples was done by the method outlined by Jackson (1949) with some modifications suggested by Pawluk (1961). The method consists of removing the organic matter with H_2O_2 and washing the samples with water. The soil was dispersed by adjusting the suspension to pH 8.0 with NaOH. The suspension was allowed to equiliberate overnight and the pH readjusted to 8.0. The separation of clay from silt and sand fractions was accomplished by repeated decantation of the upper 8 cm. of suspension after standing 6 hours and 8 minutes. The settling time of silt was calculated by Stoke's Law (Baver, 1959).

The clay fraction was flocculated with magnesium chloride followed by washing with distilled water to remove

chlorides. Free iron was removed by sodium hydrosulphite treatments and the samples were then washed with alcohol and benzene. This was followed by thorough washing with carbon disulphide (Drosdorff, 1941) removing the excess carbon disulphide with benzene (Mitchell and Mackenzie, 1954). This treatment essentially removes the sulphur particles remaining in the clay samples after hydrosulphite treatment. The samples were saturated with magnesium for X-ray analysis and with ammonium for total chemical analysis.

X-ray Analysis of Clay Minerals: The clay samples were prepared for X-ray analysis according to the method of Kittrick (1961). A few drops of clay suspension were placed on glass slides and allowed to dry by standing overnight. The clay samples were glycolated by placing the prepared slides in a saturated atmosphere of ethylene glycol in a vacuum dessicator. Duplicates of the glycolated slides of these samples were heated to 550°C. for 2 hours before running the X-rays.

A Norelco X-ray diffractometer with a high angle goniometer was used for X-ray analysis of the clays. The X-ray unit was set at 35 kilowatts, 15 milliamperes and had a copper Kα radiation with a nickel filter. A scale factor of 8 and time constant of 4 were used on the recorder. The scanning time was one degree per minute.

Cation Exchange Capacity of Clays: Cation exchange capacity was determined according to a procedure used for the exchange capacity of the soil.

Surface Areas of Clays: Total surface areas were determined on the clays after passing through a 200 mesh sieve. The procedure used for this determination is outlined by Mehra and Jackson (1959). The method is based on mono-interlayer glycerol sorption by montmorillonite at 35°C. in a vacuum of $<$ 1 mm. Hg. A 0.1 g. sample of H_2O_2-treated clay is saturated with glycerol and placed in a vacuum oven under specified conditions until a constant weight of the sample is obtained. The surface areas were calculated from the weight of the glycerol sorbed as demonstrated by Jackson (1956).

Total Fusion Analysis: Total fusion analysis was performed on NH_4-saturated clays by the method outlined by Atkinson et al. (1958). Calcium and magnesium were determined by the complexiometric titration with EDTA as described by Cheng and Bray (1951). Sodium and potassium were determined by flame photometry using the Beckman Model DU flame spectrophotometer. Total sesquioxides were determined by the gravimetric method as outlined by Kolthoff and Sandell (1953). Iron was measured colorimetrically as mentioned previously and aluminum calculated by difference between total oxides and iron oxide.

Separation of Light, Intermediate, and Heavy Minerals: The mineral fraction with a diameter between 0.1 and 0.15 millimeters was separated by wet-sieving of the soil samples. The fraction was treated with H_2O_2 to destroy the organic matter and washed with water. Free iron was removed by repeated extraction with sodium hydrosulphite. The samples were re-sieved to remove

the sulphur particles and the colloid precipitate of iron compounds that formed after the hydrosulphite treatment.

The light, intermediate, and heavy minerals were separated by the heavy liquid separation technique. A mixture of tetra-bromoethane and nitro-benzene (sp. gr. 2.70) was used for light minerals separation and tetrabromoethane (sp. gr. 2.96) was used for the heavy minerals.

Light Mineral Analysis: The chemical composition of light minerals was determined by the hydrofluoric and sulphuric acid extract method as outlined by Atkinson et al. (1958). Elemental analyses were determined by the same method as described previously except that the silica was determined by difference.

RESULTS AND DISCUSSION

Physical Analyses

Particle Size Analysis

Results of particle size analysis are reported in Table IX. The data suggest that there are textural differences between the A and B horizons of profiles 2 and 3 (Black Solonetz). The texture of the A and C horizons is silty clay and of the B horizon heavy clay. The clay content increases with depth reaching a maximum in the lower B and upper C horizons. The sand fractions are slightly higher for the surface horizons but are quite uniform in the B and C horizons. Distribution of silt content is similar to sand. The decrease in content of the silt fraction with depth in the profiles is reflected by a corresponding increase in the clay content. It is also obvious that the B horizons have a relatively higher content of fine clay than coarse clay. This increase in the fine clay content extends to a considerable depth. The difference in the amount of fine clay in the A and B horizons cannot be accounted for by simple eluviation since the A horizon, in both profiles, is too thin to provide the necessary clay. It seems more reasonable to assume that a large part of the fine clay of the B horizon is a result of variable dispersion. Since these profiles are largely sodium saturated, at lower depths the adsorbed sodium cations which enhance the adsorption of water tend to separate the unit layers completely. Such a phenomenon would result in the breakdown of the coarse particles to fine size.

TABLE IX. Particle Size Analyses and Bulk Density Values for Various Horizons of Different Profiles Sampled

Sample Number	Horizon	Depth in.	Sand Fractions v.c.s. %	c.s. %	m.s. %	f.s. %	v.f.s. %	Total Sands %	Silt %	Clay Fractions c.clay 2-0.2 μ %	f.clay 0.2 μ %	Total Clay %	Bulk Density* g./cc.
						1. Black Solodized Solonetz							
1	Ah1	1- 3	1.6	1.2	2.2	4.6	8.7	18	42	19	21	40	0.89
2	Ah2	3- 7	0.6	1.6	1.9	4.3	8.2	17	50	18	15	33	0.98
3	Ahe	7- 8	0.2	1.3	2.0	5.0	10.7	19	50	17	14	31	0.98
4	AB	8- 9	0.2	1.4	2.2	5.3	13.2	22	49	16	13	29	0.98
5	Bnt1	9-11	0.1	0.9	1.5	3.7	10.9	17	46	15	22	37	1.30
6	Bnt2	11-16	0.3	0.7	1.3	3.4	12.3	18	41	11	30	41	1.42
7	Bnt3	16-20	0.2	1.1	2.0	5.6	11.8	21	30	17	32	49	1.56
8	Bs	20-28	0.2	1.2	1.6	3.8	4.7	11	30	22	37	59	1.57
9	Cca	28-36	0.1	0.2	0.3	0.6	1.1	2	32	13	52	66	1.34
10	C	36-42	0.1	0.3	0.7	1.1	3.6	6	43	27	24	51	1.35
11	Cs	42-55	0.0	0.4	0.6	1.5	1.2	4	42	34	22	56	-
12	II C1	55-72	0.3	1.3	3.0	12.0	12.0	29	41	16	15	31	-
13	II C2	72-76	0.7	1.3	2.3	6.3	5.6	16	48	23	13	36	-

* These values are the average of duplicates

TABLE IX. (Continued)

Sample Number	Horizon	Depth in.	Sand Fractions v.c.s. %	c.s. %	m.s. %	f.s. %	v.f.s. %	Total Sands %	Silt %	Clay Fractions c.clay 2-0.2 μ %	f.clay 0.2 μ %	Total Clay %	Bulk Density g./cc.
						2. Black Solonetz							
14	Ah	0- 3	0.6	0.6	0.6	1.7	4.9	8	51	26	15	41	1.04
15	Ahe	3- 4	0.4	0.8	0.7	1.8	5.1	9	47	22	22	44	0.94
16	Surface of Bnt1*	4-10	0.4	1.0	0.9	2.2	6.7	11	45	14	30	44	-
17	Bnt1	4-10	0.2	0.6	0.7	1.5	3.3	6	31	21	42	63	1.30
18	Bnt2	10-16	0.2	0.8	0.9	1.6	3.5	7	32	16	45	61	1.39
19	Bnt3	16-24	0.2	0.5	0.5	1.1	1.9	4	25	26	46	71	1.49
20	Bs	24-30	0.1	0.4	0.5	1.0	1.4	3	28	27	42	68	1.48
21	Bsk	30-55	0.2	0.2	0.2	0.5	0.6	2	24	33	41	74	-
22	Cs	55-65	0.2	0.2	0.2	0.5	0.4	1	38	29	32	61	-
23	C1	65-72	0.1	0.1	0.1	0.1	0.2	1	33	34	32	66	-
24	C2	72-75	0.2	0.4	0.5	1.3	0.9	3	38	29	30	59	-

* Material obtained by removing the surfaces of the columns of Bnt1 horizon.

TABLE IX. (Continued)

Sample Number	Horizon	Depth in.	Sand Fractions v.c.s. %	c.s. %	m.s. %	f.s. %	v.f.s. %	Total Sands %	Silt %	Clay Fractions c.clay 2-0.2 μ %	f.clay 0.2 μ %	Total Clay %	Bulk Density g./cc.
						3. Black Solonetz							
25	Ah	0- 3	0.5	0.8	0.6	1.9	4.0	8	54	25	14	39	1.06
26	Surface of Bnt1	3- 9	0.4	0.9	0.9	2.1	5.7	10	43	18	26	43	-
27	Bnt1	3- 9	0.3	0.8	0.9	1.8	4.5	8	40	20	32	52	1.29
28	Bnt2	9-11	0.2	0.7	0.5	1.2	3.9	7	40	21	32	53	1.09
29	Bs	11-16	0.1	0.4	0.4	0.9	1.4	3	36	25	36	61	1.46
30	Cs	16-31	0.0	0.2	0.3	0.4	0.7	2	25	34	40	73	1.45
31	Csk	31-45	0.1	0.3	0.5	1.1	0.2	2	45	35	18	53	1.45
32	C1	45-55	0.0	0.3	0.3	0.6	0.5	2	45	28	26	53	1.45
33	C2	55-72	0.2	0.1	0.2	0.4	0.4	1	43	28	28	56	-
34	C3	72-75	0.3	0.7	0.9	2.2	1.8	6	44	25	25	50	-

TABLE IX. (Continued)

Sample Number	Horizon	Depth in.	Sand Fractions v.c.s. %	c.s. %	m.s. %	f.s. %	v.f.s. %	Total Sands %	Silt %	Clay Fractions c.clay 2-0.2 μ %	f.clay 0.2 μ %	Total Clay %	Bulk Density g./cc.
						4. Black Solodized Solonetz							
35	Ah	0- $2\frac{1}{2}$	0.4	0.9	0.6	2.4	8.8	13	49	10	28	38	0.75
36	Ahe	$2\frac{1}{2}$-4	0.6	0.5	0.5	2.0	9.4	13	48	11	28	39	0.80
37	Ae	4- $5\frac{1}{2}$	0.3	0.4	0.5	1.7	8.5	11	54	10	25	35	0.92
38	AB	$5\frac{1}{2}$-6	0.4	0.7	0.6	1.8	8.6	12	57	11	20	31	0.99
39	Surface of Bnt1	6-10	0.1	0.5	0.5	1.7	8.7	11	55	10	24	34	-
40	Bnt1	6-10	0.3	0.9	0.6	1.4	8.5	12	54	14	21	35	1.22
41	Bnt2	10-13	0.2	0.3	0.6	1.6	6.8	10	44	16	30	46	1.53
42	Bnt3	13-18	0.2	0.5	0.5	1.2	5.1	7	40	20	33	53	1.48
43	BC	18-24	0.2	0.6	0.5	1.2	6.3	9	51	16	24	40	1.50
44	Cs	24-31	0.2	0.4	0.6	1.3	1.0	3	49	28	29	57	1.41
45	Csk	31-40	0.1	0.6	0.7	1.4	1.1	4	44	30	23	52	1.39
46	C1	40-48	0.4	0.2	0.2	0.5	0.5	2	48	22	28	50	1.36
47	C2	48-72	0.1	0.4	0.5	1.3	1.1	3	53	27	17	44	-
48	C3	72-	0.2	0.8	1.1	2.9	2.1	7	67	17	9	26	-

TABLE IX. (Continued)

Sample Number	Horizon	Depth in.	Sand Fractions v.c.s. %	c.s. %	m.s. %	f.s. %	v.f.s. %	Total Sands %	Silt %	Clay Fractions c.clay 2-0.2 μ %	f.clay 0.2 μ %	Total Clay %	Bulk Density g./cc.
						5. Eluviated Black							
49	Ah1	0- 2	0.7	1.3	1.4	3.2	6.1	13	41	20	26	46	0.82
50	Ah2	2- 8	0.1	0.8	0.8	2.2	5.8	10	49	17	24	41	0.83
51	Ah3	8-11	0.2	0.6	0.8	2.3	6.1	10	55	25	10	35	1.11
52	Ahe	11-15	0.2	0.6	0.8	2.3	6.3	10	55	23	12	35	1.11
53	AB	15-15½	0.3	0.4	0.7	2.3	5.8	10	45	22	23	45	1.13
54	Upper Bt1	15½-17	0.1	0.4	0.6	1.7	3.7	6	35	27	32	59	1.47
55	Lower Bt1	17-22	0.3	0.8	1.3	2.8	3.2	8	34	26	32	58	1.53
56	Bt2	22-29	0.3	0.6	0.9	2.1	2.6	7	34	26	33	59	1.44
57	Bt3	29-36	0.2	0.8	1.2	2.6	2.5	7	40	31	22	53	1.42
58	BC	36-46	0.0	0.4	0.4	1.1	1.0	3	47	32	18	50	1.38
59	C1	46-52	0.2	0.3	0.5	1.4	1.2	4	48	25	23	48	-
60	C2	52-72	0.4	1.5	1.3	6.3	7.0	18	52	16	14	30	-
61	C3	72-	0.6	1.6	1.8	3.6	5.3	13	55	17	15	32	-

TABLE IX. (Continued)

Sample Number	Horizon	Depth in.	Sand Fractions v.c.s. %	c.s. %	m.s. %	f.s. %	v.f.s. %	Total Sands %	Silt %	Clay Fractions c.clay 2-0.2 μ %	f.clay 0.2 μ %	Total Clay %	Bulk Density g./cc.
						6. Orthic Black (Solodic)							
62	Ah	0- 4	0.1	0.6	0.3	0.8	2.8	5	51	29	25	54	0.80
63	AB	4- 9	0.1	0.3	0.2	0.9	2.8	5	37	34	24	58	1.03
64	Bm1	9-13	0.0	0.3	0.3	0.9	3.2	5	40	22	33	55	1.36
65	Bm2	13-18	0.1	0.3	0.3	0.7	3.8	5	41	19	35	54	1.29
66	Cca	18-28	0.1	0.2	0.2	0.4	0.8	2	28	25	45	70	1.32
67	Ck	28-41	0.1	0.9	0.6	0.6	0.3	2	22	46	30	76	1.31
68	C1	41-52	0.1	T*	T*	0.1	T*	T*	35	36	29	65	-
69	C2	52-66	0.0	0.3	0.5	1.0	0.8	3	58	18	21	39	-
70	C3	66-68	0.1	0.3	0.4	0.9	0.9	3	67	15	15	30	-

* Less than 0.05 per cent (less than 0.5 per cent in case of total sand)

TABLE IX. (Continued)

Sample Number	Horizon	Depth in.	Sand Fractions v.c.s. %	c.s. %	m.s. %	f.s. %	v.f.s. %	Total Sands %	Silt %	Clay Fractions c.clay 2-0.2 μ %	f.clay 0.2 μ %	Total Clay %	Bulk Density g./cc.
						7. Eluviated Black							
71	Ah	0- 4	0.5	0.8	1.6	7.3	9.0	19	55	17	9	26	1.00
72	Ae	4-10	0.1	0.6	1.4	10.8	11.5	24	61	14	1	15	1.59
73	Upper Bt1	10-12½	T*	0.2	0.4	2.8	4.1	8	36	18	38	56	1.47
74	Lower Bt1	12½-15	T*	0.2	0.3	2.2	3.5	6	33	19	42	61	1.55
75	Bt2	15-21	T*	0.1	0.3	1.7	3.6	6	36	20	38	58	1.54
76	Bt3	21-26	T*	0.1	0.1	1.0	3.1	4	42	23	31	54	1.86
77	BC	26-36	T*	T*	0.1	0.8	4.9	6	43	25	26	51	1.73
78	Cs	36-44	0.0	0.1	0.2	1.8	8.2	10	40	27	23	50	-
79	Csk	44-60	0.1	0.1	0.4	1.8	8.8	11	36	26	27	53	-

* Less than 0.5 per cent

To confirm this, some soil samples of known mechanical composition were sodium saturated and analyzed for their particle size composition. The results are reported in Table X. It is evident from the data that the percentage of fine clay increases with sodium saturation under a continually wetted state as well as with an alternate wetting and drying. A slight decrease in the coarse clay and silt fractions is also observed. In view of such results, it may be concluded that the large part of the fine clay in the B horizon is formed as a result of comminution of coarser particles.

The data from these profiles also indicate that a close relationship exists between clay contents and the amount of salts present in various horizons. Higher clay content was found in the horizons with high salt accumulation. It is reasonable to assume that clays in these horizons occur in a flocculated state and are much more stable than the clays occurring in horizons of low salt accumulation. The movability of clays in these horizons is greatly influenced by the type and amounts of soluble salts.

In profiles 1 and 4 (Black Solodized Solonetz) the particle size distribution pattern is similar to profiles 2 and 3 (Black Solonetz) except that the percentage of sand and silt fractions are higher. The data for these profiles indicate that there is no marked difference in the clay content in the Ae horizon and Bntl horizon. This suggests that illuviation of fine particles into lower horizons is limited. However, the lower B and upper C horizons do show a higher clay content which may be due to the degree of dispersion of fine clay in the case

TABLE X. The Effect of Sodium on the Dispersion of Soil Particles

Treatment*	Size Class of Particles			
	Sand 2-0.05 mm. %	Silt 0.05-0.002 mm. %	Coarse Clay 2-0.2 μ %	Fine Clay 0.2 μ %
1. Cooking Lake Loam				
Check	46	24	12	18
Continually wetted	45	24	11	20
Alternately wetted and dried	45	23	11	21
Continually wetted + sodium saturated	46	22	8	25
Alternately wetted and dried + sodium saturated	46	21	8	26
2. Beaverhills Loam				
Check	53	24	7	16
Continually wetted	53	23	8	16
Alternately wetted and dried	53	24	6	17
Continually wetted + sodium saturated	51	22	6	21
Alternately wetted and dried + sodium saturated	51	21	6	22

* Duration of the treatment was 6 weeks

of B horizons and the variation in the stratification of the parent material in the case of C horizons. The latter fact is apparent from the differences in the clay content of the various subdivisions in the C horizons.

Absence of marked eluviation and illuviation in profile 4 (Black Solodized Solonetz) indicates that it has not undergone severe solodization, a process which suggests that the Ae results from the degradation of upper Bnt horizons and the eluviated material accumulates in the lower horizons.

Profile 5 (Eluviated Black) has a relatively higher sand content than profile 6 (Orthic Black) and the data indicate that there is a textural variation in the parent materials of the two profiles. The higher clay content in the B horizons of profile 5 (Eluviated Black) may be due to the illuviation of fine clay from the surface horizons which are lighter in texture. There is no indication of illuviation in the B horizon of profile 6 (Orthic Black). High soluble salts may be responsible for the stabilization of the clay in upper C horizons.

Profile 7 (Eluviated Black) differs markedly from the other profiles by having a much lower clay content, particularly fine clay, in the Ae horizon. The surface horizons have considerable amounts of sand and silt which decrease with depth. There is a sudden decrease in the fine clay content of the Ae horizon followed by an abrupt increase in the upper Bt1 horizon. The increase in clay content is also evident in the lower B horizon. This suggests that there was illuviation of the displaced clay from the Ae horizon into the B horizon. The field observation also indicated that the general appearance of the upper B horizon is very similar to the Ae, suggesting that the Ae has developed by the degradation of a pre-existing upper B horizon. This follows the traditional argument given for

solodization which no doubt appears to have its application at this site in contrast to the other profiles studied.

Bulk Density

Bulk density values are given in Table IX. The data, in general, show the bulk density values to be low in the A horizons but high in the B horizons. Generally, the bulk density increases in the B horizons and decreases in the C horizons in all profiles. The values range from a minimum of 0.75 g./cc. (Ah horizon of profile 4) to a maximum of 1.86 g./cc. (Bt3 horizon of profile 7). The high values may be due to accretion of fine clay between the coarser grains as well as compaction. The low bulk densities of surface horizons may be attributed to their high organic matter contents and lack of compaction. Organic matter promotes better granulation resulting in more porous conditions in the surface horizons giving low bulk density values. This is in accordance with the views presented by Buckman and Brady (1960). These authors state that the bulk densities of clay, clay loam, and silt loam surface soils normally may range from 1.00 to as high as 1.60 g./cc. Very compact subsoils, regardless of texture, may have bulk densities as high as 2.0 g./cc. or even greater.

Colloid Movability

A considerable insight into soil dynamics may be achieved by the study of colloid movability in various horizons of a soil profile. Applied to Solonetzic soils, determinations of colloid movability may be related to the stability and permeability of the clay-pan horizons.

As indicated elsewhere in this report, the colloid movability is calculated from the reciprocal value of the coagulation plus stability factors. Thus a low value means that the colloid is highly dispersive or mobile. On the other hand, a high value indicates a low degree of dispersion of the colloids and hence low mobility.

The data for colloid movability, electrical conductivity, and exchangeable sodium percentage are shown in Table XI. It is observed from the data that the colloid movability values increase with depth in the solum. This is true for almost all the profiles studied. There appears to be a direct relationship between the colloid movability and the electrical conductivity of the various horizons. The highest values were obtained where the electrical conductivity is high. It appears that a critical conductivity value exists above which the movability of the colloids approaches zero. This limit appears to be between the conductivity values of 2 and 3. This is quite apparent from the high values of colloid movability obtained for the lower horizons which have high contents of soluble salts. The colloids in the lower B and C horizons exist in a flocculated state and are relatively stable. They resist the influence of dispersing agents and thus result in high values of colloid movability. All the Bnt horizons of the profiles studied have colloid movability values higher than 0.15.

The data indicate that there is no relationship between the exchangeable sodium percentage (ESP) and colloid movability.

TABLE XI. Movability of the Colloids in Various Horizons of Some Solonetzic Soils

Sample Number	Horizon	Depth in.	Coagulation Factor	Stability Factor	Colloid Movability	E.C. x 10^3 mmhos/cm.	ESP*
			1. Black Solodized Solonetz				
1	Ah1	1- 3	3.3	5.5	0.114	-	1.7
2	Ah2	3- 7	6.0	4.1	0.099	-	6.4
3	Ahe	7- 8	5.7	3.7	0.106	-	8.1
4	AB	8- 9	4.8	3.8	0.116	-	10.4
5	Bnt1	9-11	3.1	3.5	0.152	-	13.4
6	Bnt2	11-16	3.0	3.6	0.152	1.3	14.3
7	Bnt3	16-20	1.0	1.1	0.476	1.9	13.5
8	Bs	20-28	-	-	-	7.4	6.2
			2. Black Solonetz				
14	Ah	0- 3	4.5	3.9	0.119	-	9.6
15	Ahe	3- 4	7.5	4.8	0.081	-	14.5
16	Surface of Bnt1	4-10	3.8	2.7	0.154	-	21.3
17	Bnt1	4-10	2.8	3.1	0.169	-	24.1
18	Bnt2	10-16	0.4	0.5	1.111	4.4	38.1
19	Bnt3	16-24	-	-	-	7.8	31.5
			3. Black Solonetz				
25	Ah	0- 3	7.6	5.0	0.079	-	20.6
26	Surface of Bnt1	3- 9	2.8	2.5	0.188	1.4	24.0
27	Bnt1	3- 9	1.6	1.2	0.357	1.6	27.3
28	Bnt2	9-11	0.8	0.8	0.625	2.2	40.6
29	Bnt3	11-16	-	-	-	15.7	18.5
			4. Black Solodized Solonetz				
35	Ah	0- $2\frac{1}{2}$	4.4	5.3	0.102	-	5.9
36	Ahe	$2\frac{1}{2}$- 4	11.2	6.2	0.057	-	8.6
37	Ae	4- $5\frac{1}{2}$	8.0	3.3	0.089	-	17.4
38	AB	$5\frac{1}{2}$- 6	3.2	3.5	0.149	-	24.9
39	Surface of Bnt1	6-10	1.3	1.5	0.367	2.1	40.2
40	Bnt1	6-10	1.1	1.3	0.417	2.2	39.5
41	Bnt2	10-13	0.7	0.9	0.600	3.9	36.7
42	Bnt3	13-18	0.3	0.3	1.665	6.4	35.3

* Exchangeable sodium percentage

TABLE XI. (Continued)

Sample Number	Horizon	Depth in.	Coagulation Factor	Stability Factor	Colloid Movability	E.C. x 10^3 mmhos/cm.	ESP*
			5. Eluviated Black				
49	Ah1	0- 2	3.3	4.2	0.133	-	0.8
50	Ah2	2- 8	4.3	4.0	0.121	-	0.8
51	Ah3	8-11	4.2	4.7	0.112	-	0.9
52	Ahe	11-15	6.6	4.3	0.092	-	1.1
53	AB	15-15½	11.2	8.3	0.051	-	0.8
54	Upper Bt1	15½-17	7.5	5.3	0.078	-	0.9
55	Lower Bt1	17-22	7.8	5.0	0.078	-	1.1
56	Bt2	22-29	1.0	1.6	0.444	-	1.0
57	Bt3	29-36	1.2	1.8	0.333	-	1.0
58	BC	36-46	3.7	3.5	0.139	0.4	0.7
59	C1	46-52	4.3	4.1	0.119	0.4	0.3
			6. Orthic Black (Solodic)				
62	Ah	0- 4	3.4	3.8	0.139	-	1.1
63	AB	4- 9	4.6	3.3	0.127	-	2.5
64	Bm1	9-13	1.7	1.5	0.132	1.8	4.3
65	Bm2	13-18	0.5	1.0	0.668	2.5	4.3
			7. Eluviated Black				
71	Ah	0- 4	5.0	3.3	0.121	-	1.6
72	Ae	4-10	6.0	2.0	0.125	-	2.6
73	Upper Bt1	10-12½	5.8	4.4	0.098	-	1.5
74	Lower Bt1	12½-15	7.3	4.8	0.083	-	1.7
75	Bt2	15-21	6.0	5.6	0.086	-	2.2
76	Bt3	21-26	6.0	3.0	0.111	0.5	1.1
77	BC	26-36	4.7	2.4	0.137	0.9	1.4
78	Cs	36-44	4.8	2.6	0.135	1.5	1.2

* Exchangeable sodium percentage

Chemical Analyses

Soil Reaction

The pH values of the soils studied (see Table XII) range from 5.0 to 6.7 in the A horizons, 4.9 to 8.2 in the B horizons, and 7.6 to 8.2 in the C horizons. The lowest pH values were measured in the lower A and upper B horizons, suggesting the maximum intensity of pedogenesis at these points. The low pH values reflect low base saturation while high pH values appear to result from higher sodium and/or calcium contents. The pH values reported for soil profiles studied are in accordance with the results obtained by other workers (Bentley and Rost, 1947; Bowser et al., 1962) for similar soils.

Electrical Conductivity and Soluble Salts

The electrical conductivity and soluble cations and anions are reported in Table XII. The soluble salt content of A and some B horizons having pH values less than 7 was not determined since very low soluble salt concentrations were evident. However, upper B horizons have appreciable amounts of soluble salts even at pH values lower than 7. This is obvious from the electrical conductivity values listed for B horizons in Table XI.

There is a considerable variation in soluble salt content among the different profiles studied. In general, soluble salts increase with depth in all profiles with the exception of profile 5 (Eluviated Black). The maximum electrical conductivity occurs in the lower B and upper C horizons. The maximum levels of soluble salts occur in profiles 2 and 3

TABLE XII.

(See over)

TABLE XII. Chemical Characteristics of Some Solonetzic Soils

Sample Number	Horizon	Depth in.	pH	EC x 10^3 mmhos/cm.	Soluble Cations Na^+	Ca^{++}	Mg^{++}	Soluble Anions HCO_3^-	Cl^-	SO_4^{--}	Satn. %
					me./100 g. soil						
				1. Black Solodized Solonetz							
1	Ah1	0- 3	6.3	-	-	-	-	-	-	-	-
2	Ah2	3- 7	5.6	-	-	-	-	-	-	-	-
3	Ahe	7- 8	5.4	-	-	-	-	-	-	-	-
4	AB	8- 9	5.5	-	-	-	-	-	-	-	-
5	Bnt1	9-11	5.7	-	-	-	-	-	-	-	-
6	Bnt2	11-16	6.6	-	-	-	-	-	-	-	-
7	Bnt3	16-20	7.6	1.9	0.8	0.2	T*	0.1	T*	0.9	52.4
8	Bs	20-28	7.8	7.4	3.2	1.3	1.3	0.1	0.1	4.9	58.3
9	Cca	28-36	8.0	6.2	2.4	1.0	1.7	0.1	0.1	4.9	66.5
10	C	36-42	7.9	4.0	1.1	1.1	1.3	0.1	T*	3.4	65.4
11	Cs	42-55	7.8	6.0	2.6	1.6	1.8	0.1	0.1	5.9	80.2
12	II C1	55-72	8.0	6.0	2.4	0.6	0.7	0.1	T*	3.6	53.6
13	II C2	72-76	8.0	3.6	2.0	0.2	0.4	0.1	0.1	2.2	61.7
				2. Black Solonetz							
14	Ah	0- 3	5.1	-	-	-	-	-	-	-	-
15	Ahe	3- 4	5.0	-	-	-	-	-	-	-	-
16	Surface of Bnt1	4-10	5.1	-	-	-	-	-	-	-	-
17	Bnt1	4-10	4.9	-	-	-	-	-	-	-	-
18	Bnt2	10-16	6.9	-	-	-	-	-	-	-	-
19	Bnt3	16-24	8.2	7.8	6.2	0.2	0.8	0.2	0.2	7.2	81.1
20	Bs	24-30	8.2	12.5	7.3	1.7	3.1	0.2	0.1	12.0	80.6
21	Bsk	30-55	8.2	13.5	10.9	0.4	2.7	0.2	0.1	12.9	80.2
22	Cs	55-65	8.1	15.5	10.8	1.0	4.1	0.2	0.1	15.4	78.1
23	C1	65-72	8.1	14.0	11.1	1.6	2.5	0.2	0.2	14.4	78.0
24	C2	72-75	8.1	13.0	9.1	1.3	2.0	0.1	0.1	12.5	75.0
				3. Black Solonetz							
25	Ah	0- 3	4.9	-	-	-	-	-	-	-	-
26	Surface of Bnt1	3- 9	5.1	-	-	-	-	-	-	-	-
27	Bnt1	3- 9	5.3	-	-	-	-	-	-	-	-
28	Bnt2	9-11	7.0	-	-	-	-	-	-	-	-
29	Bs	11-16	7.9	15.7	11.6	1.5	2.7	0.1	0.1	15.5	77.0

* Less than 0.05

TABLE XII. (Continued)

Exchangeable Cations						C.E.C.		$CaCO_3$ Equiv.	Organic Carbon	Nitrogen	C/N
Ca^{++}	Mg^{++}	Na^{+}	K^{+}	H^{+*}	Al^{+++}	Calcd.**	Detd.				
Percentages of Exchangeable Cations***						me./100 g.soil		%	%	%	
1. Black Solodized Solonetz											
69.0	15.5	1.7	4.0	9.8	1.2	43.9	44.2	0.3	9.84	0.79	13
45.3	20.4	6.4	1.5	26.4	1.9	38.9	37.1	0.1	6.77	0.58	12
36.3	24.1	8.1	1.2	30.3	3.7	31.9	32.5	0.1	4.54	0.40	11
38.6	31.2	10.4	1.4	18.4	2.5	27.4	27.6	0.1	2.19	0.18	11
42.3	34.3	13.4	1.6	8.4	1.2	31.9	32.7	0.1	2.02	0.18	11
44.6	35.6	14.3	1.5	4.0	0.9	34.2	34.1	0.1	1.60	0.15	11
48.6	36.1	13.5	1.6	-	0.8	35.8	34.1	0.5	1.31	0.10	12
72.5	20.3	6.2	1.0	-	0.5	62.0	30.6	3.7	0.67	0.06	11
79.2	15.5	4.7	0.6	-	0.3	78.7	28.8	8.2	0.68	0.06	11
81.5	15.4	2.3	0.8	-	0.3	66.9	26.8	3.7	0.65	0.05	11
74.0	18.7	6.6	0.8	-	0.3	58.2	28.8	3.8	0.48	0.06	10
61.6	26.8	10.3	1.3	-	0.3	34.2	20.0	2.7	0.32	0.04	8
54.6	33.2	11.0	1.2	-	0.4	34.9	20.5	1.9	0.37	0.05	7
2. Black Solonetz											
30.1	21.9	9.6	3.7	34.6	1.2	39.7	42.8	0.1	11.45	0.95	12
18.1	22.1	14.5	1.7	43.6	4.1	38.6	40.2	0.1	11.28	0.89	13
13.6	37.7	21.3	1.1	26.2	3.6	36.6	37.5	0.1	5.17	0.44	12
13.7	36.4	24.1	1.5	23.9	5.2	40.1	42.3	0.1	2.60	0.22	12
19.3	38.7	38.1	1.5	2.5	0.8	40.0	42.1	0.1	1.97	0.17	12
31.7	35.0	31.5	1.8	-	0.8	38.3	38.8	1.7	0.94	0.07	13
34.4	51.7	13.0	0.9	-	0.3	78.2	34.1	1.6	0.74	0.05	15
44.7	29.7	23.6	1.9	-	0.4	39.0	37.5	1.7	0.72	0.05	14
71.2	10.5	17.0	1.3	-	0.3	58.1	34.0	0.9	0.71	0.05	14
50.8	17.7	29.2	2.2	-	0.4	31.6	28.4	0.9	0.70	0.06	12
44.2	29.3	24.7	1.8	-	0.3	29.4	29.0	0.7	0.56	0.05	11
3. Black Solonetz											
22.0	19.1	20.6	2.1	36.2	2.6	47.2	49.5	0.1	12.98	1.08	12
14.3	37.0	24.0	1.4	23.3	3.8	32.3	34.7	0.1	2.67	0.23	12
16.1	38.9	27.3	1.3	16.4	2.1	39.7	41.2	0.1	2.77	0.22	13
22.4	32.7	40.6	1.4	2.8	1.0	41.8	40.9	0.1	2.52	0.20	13
63.3	17.3	18.5	0.9	-	0.6	76.0	40.8	0.1	1.01	0.08	13

* Exchange acidity
** Summation of exchangeable cations
*** Percentages are based on calculated cation exchange capacities

TABLE XII. (Continued)

(See over)

TABLE XII. (Continued)

Sample Number	Horizon	Depth in.	pH	EC x 10^3 mmhos/cm.	Soluble Cations Na^+	Ca^{++}	Mg^{++}	Soluble Anions HCO_3^-	Cl^-	SO_4^{--}	Satn. %
					me./100 g. soil						
30	Cs	16-31	8.2	21.0	16.1	1.9	2.8	0.2	0.2	20.2	78.5
31	Csk	31-45	8.1	18.0	14.2	1.6	3.4	0.2	0.1	18.6	76.1
32	C1	45-55	8.0	17.5	12.3	1.6	3.5	0.1	0.1	16.8	78.0
33	C2	55-72	7.9	14.8	11.8	1.4	3.8	0.2	0.1	16.2	79.0
34	C3	72-75	7.9	16.4	12.3	1.4	3.0	0.1	0.1	15.7	76.0
				4. Black Solodized Solonetz							
35	Ah	0- 2½	5.1	-	-	-	-	-	-	-	-
36	Ahe	2½- 4	5.0	-	-	-	-	-	-	-	-
37	Ae	4- 5½	5.2	-	-	-	-	-	-	-	-
38	AB	5½- 6	5.8	-	-	-	-	-	-	-	-
39	Surface of Bnt1	6-10	6.7	-	-	-	-	-	-	-	-
40	Bnt1	6-10	6.7	-	-	-	-	-	-	-	-
41	Bnt2	10-13	7.5	5.2	3.9	T*	0.5	0.2	0.1	3.9	73.8
42	Bnt3	13-18	7.8	8.7	6.4	0.4	0.9	0.1	0.1	7.3	75.0
43	BC	18-24	8.1	11.5	7.2	0.4	2.3	0.2	0.1	9.5	70.4
44	Cs	24-31	8.2	13.0	9.2	1.2	2.8	0.1	0.1	12.6	76.0
45	Csk	31-40	8.1	8.5	6.7	1.2	2.0	0.1	0.1	9.4	78.9
46	C1	40-48	7.9	9.0	5.0	1.4	2.1	0.1	T*	8.4	78.0
47	C2	48-72	8.0	7.4	4.4	0.6	0.4	0.2	T*	4.9	79.5
48	C3	72-	7.9	8.0	5.5	1.1	1.5	0.1	T*	8.1	67.1
				5. Eluviated Black							
49	Ah1	0- 2	6.7	-	-	-	-	-	-	-	-
50	Ah2	2- 8	5.8	-	-	-	-	-	-	-	-
51	Ah3	8-11	5.7	-	-	-	-	-	-	-	-
52	Ahe	11-15	5.7	-	-	-	-	-	-	-	-
53	AB	15-15½	5.6	-	-	-	-	-	-	-	-
54	Upper Bt1	15½-17	5.4	-	-	-	-	-	-	-	-
55	Lower Bt1	17-22	5.9	-	-	-	-	-	-	-	-
56	Bt2	22-29	6.3	-	-	-	-	-	-	-	-
57	Bt3	29-36	7.0	-	-	-	-	-	-	-	-
58	BC	36-46	7.4	0.4	0.1	0.1	0.1	0.1	T*	0.1	67.2
59	C1	46-52	7.7	0.4	0.1	T*	0.1	0.1	T*	0.1	65.3
60	C2	52-72	7.6	0.4	0.1	0.1	0.1	0.1	T*	0.1	51.2
61	C3	72-	7.6	0.5	0.1	0.1	0.1	0.1	0.1	0.2	53.8

* Less than 0.05

TABLE XII. (Continued)

Exchangeable Cations						C.E.C.		$CaCO_3$ Equiv.	Organic Carbon	Nitrogen	C/N
Ca^{++}	Mg^{++}	Na^{+}	K^{+}	H^{+*}	Al^{+++}	Calcd.**	Detd.				
Percentages of Exchangeable Cations***						me./100 g.soil		%	%	%	
68.3	18.2	12.7	0.8	-	0.4	80.9	38.0	1.5	0.79	0.06	13
61.2	18.8	19.2	0.8	-	0.3	74.8	32.4	2.1	0.72	0.05	12
62.2	18.6	18.1	1.1	-	0.4	49.9	30.4	1.8	0.66	0.06	11
49.1	26.4	20.1	1.4	-	0.5	43.9	29.4	1.6	0.59	0.06	10
65.0	19.8	14.1	1.2	-	0.4	54.2	27.4	2.1	0.61	0.05	11
						4. Black Solodized Solonetz					
35.5	18.7	5.9	3.7	36.2	1.6	42.5	46.5	0.1	13.36	1.09	12
18.0	18.0	8.6	2.8	52.5	7.1	33.1	36.4	0.1	9.43	0.78	12
14.2	22.3	17.4	2.4	43.5	11.0	25.4	29.2	0.1	5.35	0.42	13
17.2	32.0	24.9	2.1	23.8	5.5	23.3	26.0	0.1	3.65	0.30	12
22.6	46.0	39.5	1.9	10.4	1.9	19.9	23.5	0.1	2.10	0.17	12
16.1	37.6	40.2	1.0	5.0	0.7	29.5	28.2	0.1	1.81	0.16	11
19.3	42.2	36.7	1.8	-	1.1	27.8	31.2	0.1	1.53	0.13	12
18.0	44.9	35.3	1.8	-	1.1	36.1	36.9	0.1	1.31	0.10	13
29.8	42.2	26.3	1.6	-	0.5	34.7	33.7	0.1	1.52	0.12	13
57.6	24.3	17.0	1.1	-	0.3	57.1	30.6	2.9	0.61	0.05	12
69.5	21.0	8.5	1.0	-	0.2	60.4	27.7	3.0	0.58	0.05	12
69.2	18.7	11.1	1.0	-	0.2	63.6	35.6	2.2	0.73	0.06	12
50.5	35.1	12.7	1.7	-	0.3	33.0	28.4	1.4	0.70	0.06	12
61.7	27.1	9.7	1.6	-	0.2	32.2	20.2	1.0	0.72	0.05	14
						5. Eluviated Black					
72.4	17.5	0.8	4.0	5.3	0.4	52.6	51.4	0.4	10.85	0.95	11
64.5	18.2	0.8	3.9	12.6	0.5	47.1	44.9	0.1	7.13	0.62	12
66.2	18.6	0.9	3.0	11.3	0.9	39.4	36.9	0.1	4.77	0.38	13
67.8	17.5	1.1	2.1	11.5	1.0	36.8	34.2	0.1	3.23	0.27	12
64.8	23.6	0.8	1.5	9.2	0.7	35.5	33.6	0.1	1.76	0.15	12
60.5	30.3	0.9	1.4	7.0	0.5	38.2	35.6	0.1	1.38	0.10	14
62.7	30.0	1.1	1.4	4.8	0.5	36.9	36.2	0.1	1.32	0.09	15
64.3	29.5	1.0	1.5	3.7	0.5	34.4	36.4	0.1	1.27	0.09	14
66.6	29.8	1.0	1.6	-	0.4	35.7	33.4	0.1	1.07	0.08	13
74.8	23.2	0.7	1.3	-	0.4	40.2	29.8	1.5	0.71	0.06	12
79.2	19.2	0.3	1.3	-	0.3	40.4	25.1	1.9	0.66	0.06	11
74.4	23.7	0.5	1.1	-	0.3	27.0	18.5	1.7	0.47	0.04	11
75.3	23.0	0.5	1.2	-	0.3	28.7	18.7	2.6	0.40	0.04	10

* Exchange acidity
** Summation of exchangeable cations
*** Percentages are based on calculated cation exchange capacities.

TABLE XII. (Continued)

(See over)

TABLE XII. (Continued)

Sample Number	Horizon	Depth in.	pH	EC x 10^3 mmhos/cm.	Soluble Cations Na^+	Ca^{++}	Mg^{++}	Soluble Anions HCO_3^-	Cl^-	SO_4^{--}	Satn. %
					me./100 g. soil						
				6. Orthic Black (Solodic)							
62	Ah	0- 4	5.8	-	-	-	-	-	-	-	-
63	AB	4- 9	6.2	-	-	-	-	-	-	-	-
64	Bm1	9-13	6.7	-	-	-	-	-	-	-	-
65	Bm2	13-18	7.7	2.5	1.0	0.2	0.9	0.2	T*	1.7	64.8
66	Cca	18-28	8.0	6.0	2.2	1.4	2.8	0.2	0.1	6.2	74.4
67	Ck	28-41	8.0	5.0	1.3	1.4	3.2	0.1	T*	6.0	70.0
68	C1	41-52	8.0	9.5	3.1	1.8	5.0	0.2	0.1	9.1	80.5
69	C2	52-66	8.0	8.0	2.8	1.3	4.3	0.1	0.1	8.6	69.9
70	C3	66-68	7.9	8.5	3.1	1.2	3.9	0.1	T*	7.9	62.3
				7. Eluviated Black							
71	Ah	0- 4	6.0	-	-	-	-	-	-	-	-
72	Ae	4-10	6.6	-	-	-	-	-	-	-	-
73	Upper Bt1	10-12½	5.1	-	-	-	-	-	-	-	-
74	Lower Bt1	12½-15	4.9	-	-	-	-	-	-	-	-
75	Bt2	15-21	5.0	-	-	-	-	-	-	-	-
76	Bt3	21-26	7.3	0.5	0.2	0.2	0.1	0.1	0.1	0.3	68.2
77	BC	26-36	7.6	0.9	0.2	0.2	0.3	0.2	0.1	0.4	62.5
78	Cs	36-44	7.8	1.5	0.2	0.4	0.3	0.2	0.1	0.6	61.9
79	Csk	44-60	7.8	1.5	0.3	0.4	0.4	0.2	0.2	0.7	63.6
80	C1	60-72	-	3.0	0.3	1.6	1.3	0.1	0.1	2.5	66.3
81	C2	72-84	-	3.1	0.3	1.6	1.3	0.1	0.1	3.1	66.4
82	C3	84-97	-	3.4	0.3	1.6	1.4	0.1	0.1	3.2	60.2
83	C4	97-107	-	3.5	0.3	0.9	1.3	0.1	0.1	2.2	52.4
84	C5	107-117	-	3.7	0.3	0.9	1.3	0.1	0.1	2.2	44.2
85	C6	117-125	-	3.5	0.3	0.8	1.3	0.1	0.1	2.4	43.9
86	C7	125-135	-	3.4	0.3	0.8	1.2	0.1	0.1	2.3	41.2
87	C8	135-141	-	2.4	0.2	0.4	0.4	T*	0.1	1.1	34.5

* Less than 0.05

TABLE XII. (Continued)

Exchangeable Cations						C.E.C.		$CaCO_3$ Equiv.	Organic Carbon	Nitrogen	C/N
Ca^{++}	Mg^{++}	Na^{+}	K^{+}	H^{+*}	Al^{+++}	Calcd.**	Detd.				
Percentages of Exchangeable Cations***						me./100 g.soil		%	%	%	
6. Orthic Black (Solodic)											
39.9	39.3	1.1	3.7	16.0	0.3	51.7	51.0	0.1	7.97	0.75	11
32.0	52.9	2.5	2.2	10.5	0.3	51.9	48.5	0.1	6.65	0.59	11
37.6	52.5	4.3	2.0	3.7	0.3	37.6	40.1	0.1	3.80	0.32	12
57.0	45.7	4.3	2.0	-	0.8	38.2	32.2	0.7	1.37	0.13	11
74.7	20.6	3.5	1.2	-	0.4	63.8	34.4	3.5	0.59	0.07	11
77.0	20.6	1.4	1.0	-	0.2	65.0	29.4	3.7	0.54	0.05	12
72.2	24.2	2.2	1.3	-	0.4	65.6	36.7	3.0	0.47	0.05	11
78.3	18.5	2.4	0.8	-	0.2	67.4	22.3	2.2	0.47	0.05	9
75.6	20.9	2.4	1.1	-	0.2	48.2	18.0	1.6	0.45	0.05	9
7. Eluviated Black											
41.1	41.1	1.6	2.4	13.8	1.2	37.0	38.2	0.1	8.19	0.62	13
65.8	13.2	2.6	1.3	17.1	6.0	7.6	7.5	0.1	0.97	0.05	19
42.1	38.4	1.5	0.7	17.3	3.3	40.4	39.1	0.1	1.09	0.09	12
43.4	39.1	1.7	1.2	14.6	3.7	41.7	42.4	0.1	1.02	0.08	13
44.7	40.8	2.2	1.2	11.1	3.8	40.7	41.4	0.1	1.12	0.07	16
55.6	42.5	1.1	0.8	-	1.5	34.8	32.4	0.7	0.93	0.06	16
66.7	31.2	1.4	0.7	-	0.8	44.5	28.2	4.2	0.67	0.05	14
71.2	26.8	1.2	0.8	-	0.3	47.6	28.0	4.3	0.62	0.04	15
69.5	28.4	1.2	0.9	-	0.3	42.3	28.8	4.4	0.64	0.04	16
-	-	-	-	-	-	-	-	-	-	-	-
-	-	-	-	-	-	-	-	-	-	-	-
-	-	-	-	-	-	-	-	-	-	-	-
-	-	-	-	-	-	-	-	-	-	-	-
-	-	-	-	-	-	-	-	-	-	-	-
-	-	-	-	-	-	-	-	-	-	-	-
-	-	-	-	-	-	-	-	-	-	-	-
-	-	-	-	-	-	-	-	-	-	-	-

* Exchange acidity
** Summation of exchangeable cations
*** Percentages are based on calculated cation exchange capacities

(Black Solonetz), with lesser amounts in profiles 1 and 4 (Black Solodized Solonetz), and the least in profiles 5 and 7 (Eluviated Black). Such a distribution pattern of soluble salts essentially reflects the degree of pedogenic development of these profiles. Profile 7 (Eluviated Black) shows a high soluble salt content only at considerable depth indicating the downward leaching of the salts. Profile 6 (Orthic Black) has appreciable amounts of soluble salts, following the salt distribution pattern of other profiles but lacks the Solonetzic morphology. However, this profile does have the chemical criteria adopted by Canadian Soil Survey Committee as characteristic of Solonetzic soils. This profile, therefore, was classified as Solodic Orthic Black which is a tentative name proposed for such soils.

Soluble sodium is the dominant cation in all the profiles studied except in profiles 6 and 7 (Orthic Black and Eluviated Black) where magnesium is dominant. Sulphate forms the major bulk of the soluble anions of all the profile horizons studied. Very little chlorides and bicarbonates were measured and there is relatively no difference in the amount of these anions among the various profiles. No soluble carbonates were detected. The results reported are in agreement with those found by other workers (Bowser et al., 1962). These workers reported sodium sulphate to be the principal salt present in the saturation extract of Solonetzic soils of this region.

The saturation percentage of soil (Table XII) may characterize soil texture and moisture retention (U.S. Salinity Laboratory Staff, 1954). In this study the saturation percentage was used to convert the concentration of soluble salts (me./l.) in the saturation extract to concentration in terms of soil weight (me./100 g.). The saturation percentage varies from

34.5 (in the C horizon of profile 7) to 80.6 (in the B horizon of profile 2). Saturation percentages for soils may vary because of differences in kind and amount of clay, kind and amount of organic matter, and the amount of salts present in the soil.

Organic Carbon, Nitrogen, and Carbon : Nitrogen Ratio

The level of organic carbon and nitrogen in any soil reflects the content and degree of decompostion of organic matter present. Variation in organic matter content in the surface horizons can generally be related to the differences in the types of vegetation and the local climatic conditions.

The data in Table XII show that the A horizons of all profiles studied have a high organic carbon content which decreases progressively with depth through the sola. The pattern of nitrogen distribution is very similar to that of organic carbon. It is interesting to note that the organic carbon and nitrogen content in the Ae horizon of profile 4 (Black Solodized Solonetz) is much higher than the underlying B horizon. Similar results are evident in the case of profile 1 (Black Solodized Solonetz).

In contrast to profiles 1 and 4 (Black Solodized Solonetz), the data on profile 7 (Eluviated Black) indicate that the percentage of organic carbon and nitrogen is lower in the Ae horizon than the adjacent Bnt horizon. This apparently shows that the Ae horizon of this profile has lost its organic matter as a result of eluviation with a corresponding accumulation of this material in the adjacent B horizon. This also confirms the suggestion that the profile at this site had experienced a severe

solodization which is well supported by its mineralogical composition, which will be discussed later.

The carbon to nitrogen ratios in these soils vary from 7 (in the C horizon of profile 1) to 19 (in the Ae horizon of profile 7). The ratio ranges from 11 to 13 in the Ah horizons of all the profiles. There is a slightly narrower ratio in the B horizons of the Solonetzic profiles (1 to 4). Considering the carbon to nitrogen ratio of Ah horizons of the soils studied, it may be concluded that all these profiles possess Chernozemic Ah horizons. The carbon to nitrogen ratio in Chernozemic Ah horizons, as described in the Canadian Soil Classification, is 17 or less if virgin and usually does not exceed 13 if cultivated.

Calcium Carbonate Equivalent

The distribution pattern of calcium carbonate (Table XII) is similar in all the profiles studied. There is very little carbonate in the A and upper B horizons. The maximum carbonate content of 8.2 per cent was measured in the Cca horizon of profile 1 (Black Solodized Solonetz). It is also evident that the horizon of salt accumulation overlies the horizon of lime concentration in all the profiles studied. This suggests that these profiles have been resalinized by the upward movement of salts with the seasonal fluctuation in depth to the capillary fringe. Similar results are reported by other workers (Bowser et al., 1962).

Cation Exchange Capacity and Exchangeable Cations

The cation exchange capacity depends mainly on the content and the kind of exchange material. In general, the

cation exchange capacities (Table XII) parallel the distribution of clay in the profiles studied. High cation exchange capacities of surface horizons can be attributed to the presence of high organic matter content. The cation exchange capacity as determined by summation differs from that found by direct determination. The large differences for the lower B and C horizons may be attributed to the presence of free calcium carbonate and soluble salts that are dissolved in the leaching solution and is added to the exchangeable cations. This is in agreement with the results obtained by other workers (Kelley, 1948) who have shown that soluble salts and calcium carbonate are more readily soluble in ammonium acetate solution than in water. In other horizons cation exchange capacity found by ammonia distillation was generally lower than that found by summation. Similar results for such soils have been reported by other workers (Mathieu, 1960; Bentley and Rost, 1947).

The determination of exchangeable cations on the exchange complex of the soil horizons reflects partially the distribution of the cations as affected by the genetic processes. Exchangeable calcium percentage decreases from the surface horizon to a minimum in the B horizon and then increases with depth to a maximum in the C horizon of profiles 1 to 4 (Black Solonetz and Black Solodized Solonetz). A somewhat reverse order is followed by exchangeable magnesium and sodium. The exchangeable sodium content is higher in the B than in either the A or C horizons. It is also noted that the A horizons of these profiles have much higher exchangeable sodium than the A horizons of profiles 5 and 7 (Eluviated Black). The Ahe and

Ah horizons of profiles 2 and 3 (Black Solonetz) have exchangeable sodium percentages of 14.5 and 20.5, respectively, which exceeds the limit proposed for the separation of Solonetzic soils from other Great Soil groups. Similarly, the Ae horizon of profile 4 (Black Solodized Solonetz) has an exchangeable sodium percentage of 17.4. In spite of higher exchangeable sodium content in these horizons, the pH does not exceed 5.2.

Exchangeable magnesium follows a trend very similar to exchangeable sodium in all the profiles studied. The highest exchangeable magnesium content is in the AB and upper B horizons of profile 6 (Orthic Black) where it exceeds 50 per cent of the total exchangeable cations. Soluble magnesium is also higher in this profile than in the other profiles studied. Exchangeable calcium in profiles 5 and 7 (Eluviated Black) is uniformly distributed through the entire sola but tends to increase in the C horizons. This is due apparently to the presence of a high calcium carbonate content in these horizons. Exchangeable sodium in profiles 5 and 7 remains fairly uniform but there is a slight increase in its content in the B horizon of profile 6. Exchangeable potassium is distributed fairly uniformly throughout the entire depths of all the profiles studied. There is some indication that the exchangeable potassium increases slightly in the surface horizons. This can be attributed to the more acidic nature of these horizons. Buckman and Brady (1960) state that weathering of illite to montmorillonite under acidic environments is accompanied by a considerable release of potassium which can replace other exchangeable cations.

Considering the distribution of exchangeable cations, the intensity of solodization in the various profiles in Solonetzic sequence in this study may be expressed as follows: Profile 7 > profile 1 > profile 4 > profile 2 > profile 3.

The morphological features of these profiles observed in the field confirm the above sequence.

Profile 5 does not meet the chemical criteria of Solonetzic soils since exchangeable sodium is less than 12 per cent and exchangeable sodium plus magnesium is less than 50 per cent. This profile must be classed as Eluviated Black in the Chernozemic Order. Profile 6 has more than 50 per cent exchangeable magnesium plus sodium but does not exhibit the typical morphology defined for Solonetzic soils. This profile is considered to be transitional between the Solonetzic and Chernozemic Orders. It is, therefore, called Orthic Black (Solodic).

Profile 7 (Eluviated Black) has a low content of sodium but shows a morphology typical of Solonetzic soils. However, it contains a considerable amount of exchangeable magnesium. A high content of exchangeable magnesium has been considered, by many workers, as a factor contributing to the development of the Solonetz structure. This subject has been discussed very thoroughly by Bentley and Rost (1947) as mentioned previously.

Eaton and Horton (1940) found that the moisture equivalent values obtained for Ca-saturated and Mg-saturated soils were practically identical and were much lower in magnitude (frequently one-half) than the corresponding values for

Na-saturated soils. Smith et al. (1949) concluded from their experiments involving rate of capillary movement of water in soils as affected by exchangeable ions that addition of magnesium does not cause any appreciable deterioration of the physical properties of high calcium soils. The data obtained from such experiments as those cited lead one to suspect that exchangeable magnesium may not be held responsible for the development of sharply delineated textural B horizons of Solonetzic soils.

The data for profile 7 (Table XII) suggest that, earlier in its evolution, exchangeable sodium was higher in concentration closer to the surface than indicated at the present time. This assumption is well supported by the indications that the soils of the surrounding area are associated with Solodized Solonetz (Bowser et al., 1962), and morphologically have characteristics of Solods. It has also been established that these Solonetzic soils have a high content of sodium salts. In all probability, the sodium salts, being relatively more soluble, have leached down to lower depths. Consequently, the ratio of exchangeable ions in the upper horizons has shifted with time towards higher proportions of divalent cations.

Equilibrium between solution cations and adsorbed cations is greatly affected by leaching (Kelley, 1955). As the concentration of cations in solution decreases through leaching of a soil containing soluble salts, the activities of divalent cations increase more rapidly than those of monovalent cations. Consequently, exchangeable sodium may be replaced by calcium or magnesium merely by diluting the soil solution. If leached thoroughly, the exchange complex of calcareous or

gypsiferous alkali soils may be converted from sodium to calcium and/or magnesium-dominated systems. Such a sequence seems to be evident in the case of profile 7. Typical Solonetzic morphology, as observed in this profile, probably reflects past chemical regimes other than those existing presently.

Exchangeable hydrogen (exchange acidity) as reported in Table XII is a measure of hydrogen ions displaced from the exchange complex as well as hydrogen ions released by the hydrolysis of exchangeable hydrated aluminum ions. Aluminum plays a considerable role in developing soil acidity. The A horizons of the profiles in Solonetzic sequence have appreciable amounts of exchangeable aluminum. The highest percentage of exchangeable aluminum was measured in the Ae horizon of profile 7 (Eluviated Black) where it contributes approximately 35 per cent to the total exchange acidity. The Ae horizon of profile 4 (Black Solodized Solonetz) has 25 per cent of its exchange acidity due to exchangeable aluminum. In general, the exchangeable aluminum is fairly high for the horizons which have undergone solonetzic degradation.

In recent years considerable work has been done on the influence of both aluminum and hydrogen on soil acidity. Russell (1960) points out that acid mineral soils are aluminum and not hydrogen soils. He states further that aluminum liberated when acid soils are leached with neutral salt solutions contributes markedly to the exchange acidity determined by titrating the leachate to a neutral end point.

High exchange acidity values in the various horizons of the profiles studied may be indicated by their low pH.

However, it is noticed that although the lowest pH was determined in upper B horizons, the highest exchange acidity was measured in the A horizons.

A great variability in exchange acidity content results with different extracting reagents buffered at different pH values. This, however, depends on the nature of the exchange complex associated with a particular soil. This is due to the fact that various colloidal materials differ in the degree of dissociation of their adsorbed hydrogen at different pH values. For example, the adsorbed hydrogen of the organic complex dissociates in the soil solution with comparative ease at higher pH values. It has been suggested that the different acid silicate clays -- the kaolinite, montmorillonite, and hydrous mica types -- dissociate to somewhat different degrees, the kaolinite least and the montmorillonite greatest (Buckman and Brady, 1960). This difference in dissociations arises from the types of exchange sites associated with these minerals. While in montmorillonite the exchange sites are due mainly to isomorphous substitution (permanent charges), in kaolinite the exchange sites mainly result from broken bonds and are pH-dependent.

Two methods for measuring the exchange acidity are compared in Table XIII. It is observed from the data that more hydrogen was extracted with triethanolamine ($BaCl_2$), pH 8.1 than with barium acetate, pH 7.0. It is interesting to note that this variation is greatest for the surface horizons where the organic matter is the major part of the exchange complex as indicated by their higher percentage of organic carbon. Pawluk and Carson (1963) suggest that the high exchange acidity in the

TABLE XIII. A Comparison of Two Methods for Determining Exchange Acidity

Sample Number	Horizon	Depth in.	pH	Exchange acidity me./100 g. $BaCl_2$-Trieth. pH 8.1	Exchange acidity me./100 g. $Ba(C_2H_3O_2)_2$ pH 7.0	C.E.C.* me./100 g.	Organic Carbon %
				1. Black Solodized Solonetz			
1	Ah1	1- 3	6.3	19.7	4.3	44.2	9.84
2	Ah2	3- 7	5.6	27.6	10.3	37.1	6.77
3	Ahe	7- 8	5.4	25.0	9.7	32.5	4.54
4	AB	8- 9	5.5	12.9	5.0	27.6	2.19
5	Bnt1	9-11	5.7	8.5	2.7	32.7	2.02
6	Bnt2	11-16	6.6	6.4	1.4	34.1	1.60
7	Bnt3	16-20	7.6	3.4	-	34.1	1.31
8	Bs	20-28	7.8	1.0	-	30.6	0.67
9	Cca	28-36	8.0	0.8	-	28.8	0.68
10	C	36-42	7.9	1.4	-	26.8	0.65
11	Cs	42-55	7.8	1.1	-	28.8	0.48
12	II C1	55-72	8.0	1.7	-	20.0	0.32
13	II C2	72-76	8.0	1.7	-	20.5	0.37
				2. Black Solonetz			
14	Ah	0- 3	5.1	22.0	13.7	42.8	11.45
15	Ahe	3- 4	5.0	39.0	16.9	40.2	11.28
16	Surface of Bnt1	4-10	5.1	22.7	9.6	37.5	5.17
17	Bnt1	4-10	4.9	26.0	9.6	42.3	2.60
18	Bnt2	10-16	6.9	7.0	1.0	42.1	1.97
19	Bnt3	16-24	8.2	2.4	-	42.1	1.97
20	Bs	24-30	8.2	2.0	-	34.1	0.74
21	Bsk	30-55	8.2	2.2	-	37.5	0.72
22	Cs	55-65	8.1	2.0	-	34.0	0.71
23	C1	65-72	8.1	2.0	-	28.4	0.70
24	C2	72-75	8.1	2.0	-	29.0	0.56
				3. Black Solonetz			
25	Ah	0- 3	4.9	34.1	17.1	49.5	12.98
26	Surface of Bnt1	3- 9	5.1	15.0	7.5	41.2	2.67
27	Bnt1	3- 9	5.3	15.8	6.5	34.7	2.77
28	Bnt2	9-11	7.0	6.3	1.2	40.9	2.52
29	Bnt3	11-16	7.9	3.1	-	40.8	1.01

* $NH_4C_2H_3O_2$ method (pH 7.0)

TABLE XIII. (Continued)

Sample Number	Horizon	Depth in.	pH	Exchange acidity me./100 g. $BaCl_2$-Trieth. pH 8.1	Exchange acidity me./100 g. $Ba(C_2H_3O_2)_2$ pH 7.0	C.E.C.* me./100 g.	Organic Carbon %
30	Cs	16-31	8.2	0.3	-	38.0	0.79
31	Csk	31-45	8.1	0.1	-	32.4	0.72
32	C1	45-55	8.0	0.1	-	30.4	0.66
33	C2	55-72	7.9	0.1	-	29.4	0.59
34	C3	72-75	7.9	0.2	-	27.4	0.61
			4. Black Solodized Solonetz				
35	Ah	0- 2½	5.1	30.0	4.3	46.5	13.36
36	Ahe	2½- 4	5.0	32.6	10.3	36.4	9.43
37	Ae	4- 5½	5.2	24.8	9.7	29.2	5.35
38	AB	5½- 6	5.8	13.8	5.0	26.0	3.65
39	Surface of Bnt1	6-10	6.7	7.3	2.7	23.5	2.10
40	Bnt1	6-10	6.7	7.2	1.4	28.2	1.81
41	Bnt2	10-13	7.5	3.4	-	31.2	1.53
42	Bnt3	13-18	7.8	3.0	-	36.9	1.31
43	BC	18-24	8.1	2.0	-	33.7	1.52
44	Cs	24-31	8.2	0.2	-	30.6	0.61
45	Csk	31-40	8.1	0.3	-	27.6	0.58
46	C1	40-48	7.9	0.7	-	35.6	0.73
47	C2	48-72	8.0	0.6	-	28.4	0.70
48	C3	72-	7.9	0.7	-	20.2	0.72
			5. Eluviated Black				
49	Ah1	0- 2	6.7	12.2	2.8	51.4	10.85
50	Ah2	2- 8	5.8	16.4	5.9	44.9	7.13
51	Ah3	8-11	5.7	16.2	4.5	36.9	4.77
52	Ahe	11-15	5.7	13.4	4.2	34.2	3.23
53	AB	15-15½	5.6	10.3	3.3	33.6	1.76
54	Upper Bt1	15½-17	5.4	9.3	2.7	35.6	1.38
55	Lower Bt1	17-22	5.9	7.4	1.8	36.2	1.32
56	Bt2	22-29	6.3	6.3	1.3	36.4	1.27
57	Bt3	29-36	7.0	4.1	-	33.4	1.07
58	BC	36-46	7.4	2.9	-	29.8	0.71
59	C1	46-52	7.7	2.3	-	25.7	0.66
60	C2	52-72	7.6	2.2	-	18.5	0.47
61	C3	72-	7.6	1.8	-	18.7	0.40

* $NH_4C_2H_3O_2$ method (pH 7.0)

TABLE XIII. (Continued)

Sample Number	Horizon	Depth in.	pH	Exchange acidity me./100 g. $BaCl_2$-Trieth. pH 8.1	Exchange acidity me./100 g. $Ba(C_2H_3O_2)_2$ pH 7.0	C.E.C.* me./100 g.	Organic Carbon %
				6. Orthic Black (Solodic)			
62	Ah	0- 4	5.8	21.4	8.3	51.0	7.97
63	AB	4- 9	6.2	16.8	5.4	48.5	6.65
64	Bm1	9-13	6.7	7.3	1.4	40.1	3.80
65	Bm2	13-18	7.7	3.1	-	32.2	1.37
66	Ca	18-28	8.0	1.6	-	34.4	0.59
67	Ck	28-41	8.0	1.1	-	29.4	0.54
68	C1	41-52	8.0	0.7	-	36.7	0.47
69	C2	52-66	8.0	1.0	-	22.3	0.47
70	C3	66-68	7.9	1.1	-	18.0	0.45

* $NH_4C_2H_3O_2$ method (pH 7.0)

surface horizons rich in organic matter is associated with the dissociation of -COOH and -OH groups at higher pH values of the extracting solution.

Free Oxides

The data in Table XIV show the percentage free oxides in the various profile horizons. Easily extractable oxides in soil profiles usually result from the dissolution of inorganic soil mineral constituents and consequently reflect to some extent the degree of chemical weathering which has taken place. In general, the content of hydrous iron oxide is low in the surface horizons and shows a gradual increase with the depth in the profile. The Ae horizon of profile 7 (Eluviated Black) has the lowest content of free iron oxide but its concentration is much higher in the adjacent B horizon attaining maximum concentration in the lower B horizon. It appears that these oxides are leached from the surface horizons under acidic conditions and are precipitated in the lower horizons at higher pH values. The presence of calcium carbonate, gypsum, and soluble salts in these horizons appear to play a considerable role in the distribution of these oxides.

Although the total amounts of aluminum oxide in various horizons are relatively small, yet the higher contents are observed in more acid horizons. This is probably due to chemical weathering of clay and/or light minerals as indicated by their chemical analyses (Tables XV and XVIII). Aluminum oxides are almost uniformly distributed in the lower horizons.

TABLE XIV. Extractable Oxides in Some Solonetzic Soils

Sample Number	Horizon	Depth in.	Fe_2O_3 %	SiO_2 %	Al_2O_3 %
		1. Black Solodized Solonetz			
1	Ah1	1- 3	1.43	0.32	0.09
2	Ah2	3- 7	1.46	0.45	0.19
3	Ah3	7- 8	1.34	0.29	0.20
4	AB	8- 9	1.44	1.34	0.14
5	Bnt1	9-11	1.53	0.34	0.19
6	Bnt2	11-16	1.64	0.25	0.19
7	Bnt3	16-20	1.68	0.16	0.10
8	Bs	20-28	1.57	0.14	0.08
9	Cca	28-36	1.53	0.05	0.05
10	C	36-42	1.82	0.03	0.06
11	Cs	42-55	2.04	0.03	0.05
12	II C1	55-72	1.64	0.03	0.04
13	II C2	72-76	2.02	0.05	0.04
		2. Black Solonetz			
14	Ah	0- 3	1.18	1.84	0.13
15	Ahe	3- 4	1.14	1.05	0.10
16	Surface of Bnt1	4-10	1.53	0.38	0.32
17	Bnt1	4-10	2.22	0.28	0.16
18	Bnt2	10-16	1.62	0.32	0.11
19	Bnt3	16-24	1.70	0.21	0.11
20	Bs	24-30	1.78	0.19	0.11
21	Bsk	30-55	1.82	0.19	0.10
22	Cs	55-65	1.97	0.18	0.10
23	C1	65-72	2.15	0.19	0.06
24	C2	72-75	2.32	0.18	0.06
		3. Black Solonetz			
25	Ah	0- 3	1.22	0.34	0.11
26	Surface of Bnt1	3- 9	1.68	0.19	0.16
27	Bnt1	3- 9	1.76	0.18	0.16
28	Bnt2	9-11	1.70	0.21	0.19
29	Bs	11-16	2.00	0.16	0.16
30	Cs	16-31	1.75	0.15	0.06
31	Csk	31-45	1.82	0.21	0.04
32	C1	45-55	2.13	0.15	0.04
33	C2	55-72	2.20	0.18	0.04
34	C3	72-75	2.22	0.15	0.03

TABLE XIV. (Continued)

Sample Number	Horizon	Depth in.	Fe_2O_3 %	SiO_2 %	Al_2O_3 %
		4. Black Solodized Solonetz			
35	Ah	0- $2\frac{1}{2}$	0.93	1.05	0.06
36	Ahe	$2\frac{1}{2}$- 4	1.40	0.72	0.12
37	Ae	4- $5\frac{1}{2}$	1.39	0.37	0.30
38	AB	$5\frac{1}{2}$- 6	1.36	1.07	0.30
39	Surface of Bnt1	6-10	1.53	0.32	0.26
40	Bnt1	6-10	1.52	0.32	0.21
41	Bnt2	10-13	1.63	0.34	0.20
42	Bnt3	13-18	1.70	0.29	0.14
43	BC	18-24	1.49	0.33	0.13
44	Cs	24-31	1.64	0.29	0.06
45	Csk	31-40	2.06	0.25	0.03
46	C1	40-48	2.07	0.24	0.03
47	C2	48-72	2.23	0.19	--
48	C3	72-	2.30	0.19	--
		5. Eluviated Black			
49	Ah1	0- 2	1.47	0.48	0.06
50	Ah2	2- 8	1.49	0.38	0.12
51	Ah3	8-11	1.59	0.30	0.16
52	Ahe	11-15	1.61	0.29	0.14
53	AB	15-$15\frac{1}{2}$	1.80	0.46	0.16
54	Upper Bt1	$15\frac{1}{2}$-17	2.04	0.41	0.17
55	Lower Bt1	17-22	2.05	0.34	0.12
56	Bt2	22-29	2.07	0.34	0.10
57	Bt3	29-36	2.10	0.19	0.06
58	BC	36-46	2.18	0.21	0.06
59	C1	46-52	2.26	0.21	0.05
60	C2	52-72	2.09	0.20	0.03
61	C3	72-	2.00	0.19	0.03
		6. Orthic Black (Solodic)			
62	Ah	0- 4	1.39	1.19	0.06
63	AB	4- 9	1.57	0.36	0.10
64	Bm1	9-13	1.47	0.29	0.06
65	Bm2	13-18	1.44	0.37	0.09

TABLE XIV. (Continued)

Sample Number	Horizon	Depth in.	Fe_2O_3 %	SiO_2 %	Al_2O_3 %
66	Cca	18-28	1.44	0.29	0.05
67	Ck	28-41	1.59	0.25	0.04
68	C1	41-52	1.57	0.41	0.04
69	C2	52-66	2.15	0.38	0.03
70	C3	66-68	2.29	0.34	0.03
		7. Eluviated Black			
71	Ah	0- 4	1.16	1.05	0.12
72	Ae	4-10	0.42	0.10	0.06
73	Upper Bt1	10-12½	1.79	0.25	0.20
74	Lower Bt1	12½-15	2.15	0.29	0.22
75	Bt2	15-21	2.43	0.29	0.14
76	Bt3	21-26	1.92	0.19	0.04
77	BC	26-36	1.86	0.21	0.03
78	Cs	36-44	1.88	0.24	0.03
79	Csk	44-60	1.86	0.21	0.03

The content of free silica is relatively high in the surface horizons with a gradual decrease with downward progression in the solum. The distribution of silica is fairly uniform in the C horizons of all profiles studied. A similar trend was noticed by Gedroiz (quoted by Joffe, 1949) in Solonetzic soils. Exceptionally low amounts of silica in the Ae horizon of profile 7 (Eluviated Black) suggests that silica as well as sesquioxides may be leached out of the solodized horizon. The accumulation of silica in the Ae may not be considered as a trustworthy index of solodization since the upward movement of alkali may cause the separation of silica in this horizon (Bazilevich, quoted by Joffe, 1949). Rost and Maehl (1943) report more soluble silica in some solodized soils which had no soluble salts. The findings of these workers are in agreement with the results obtained in this study. The surface horizons (with little or no soluble salts) of all profiles show a high content of silica.

It is interesting to note that the surface horizon of profile 2 (Black Solonetz) is rich in silica. It appears to indicate that with the solonization process, as in all pedogenic processes, some dissolution of minerals occurred.

Although the distribution pattern of free oxides in a soil profile partly explains the nature of the solodization process, yet much remains to be learned in this field. The form in which sesquioxides and silica migrate in the profile is still a debatable question. The subject requires special research. However, the methods used for extracting these oxides take into account their ionic soluble forms. But this does not

exclude the possibility that these compounds may migrate in the form of colloidal solutions or complex compounds.

Mineralogical Analyses

X-ray and Chemical Analyses of Clays

X-ray patterns for the total clays in the selected horizons of the profiles under study are shown in Figures 2 to 8. The clays were Mg-saturated and the analyses conducted on glycolated and heated samples. Chemical analyses which were conducted on NH_4-saturated clays are given in Table XV.

The X-ray analyses of these soils indicate that montmorillonite is the dominant clay mineral with small quantities of illite and kaolinite except in the case of profile 7 where kaolinite almost equals montmorillonite in the solodized horizon. Montmorillonite exhibits a strong X-ray diffraction peak at 5.4^{o} upon glycol solvation and collapses to 8.8^{o} upon heating to 550^{o}C. The diffraction peak for illite appears at 8.8^{o} in the case of glycolated as well as heated samples. The 12.4^{o} peak which disappears upon heating the samples to 550^{o}C. is indicative of kaolinite. The diffraction peaks for montmorillonite, in many cases, are skewed towards the region of increasing diffraction angle (between 8.8^{o} and 5.4^{o}). This may be due to random interstratification of 10 Å (8.8^{o}), 14 Å (6.3^{o}), and 18 Å (4.9^{o}) layers (Brindley, 1951; Grim, 1953; Jackson, 1956). The interstratification of these layers is quite apparent from the X-ray patterns of heated samples. The B horizons of these soils show the sharpest and most intense montmorillonite X-ray diffraction lines except in the case of profiles 2, 3, and 4.

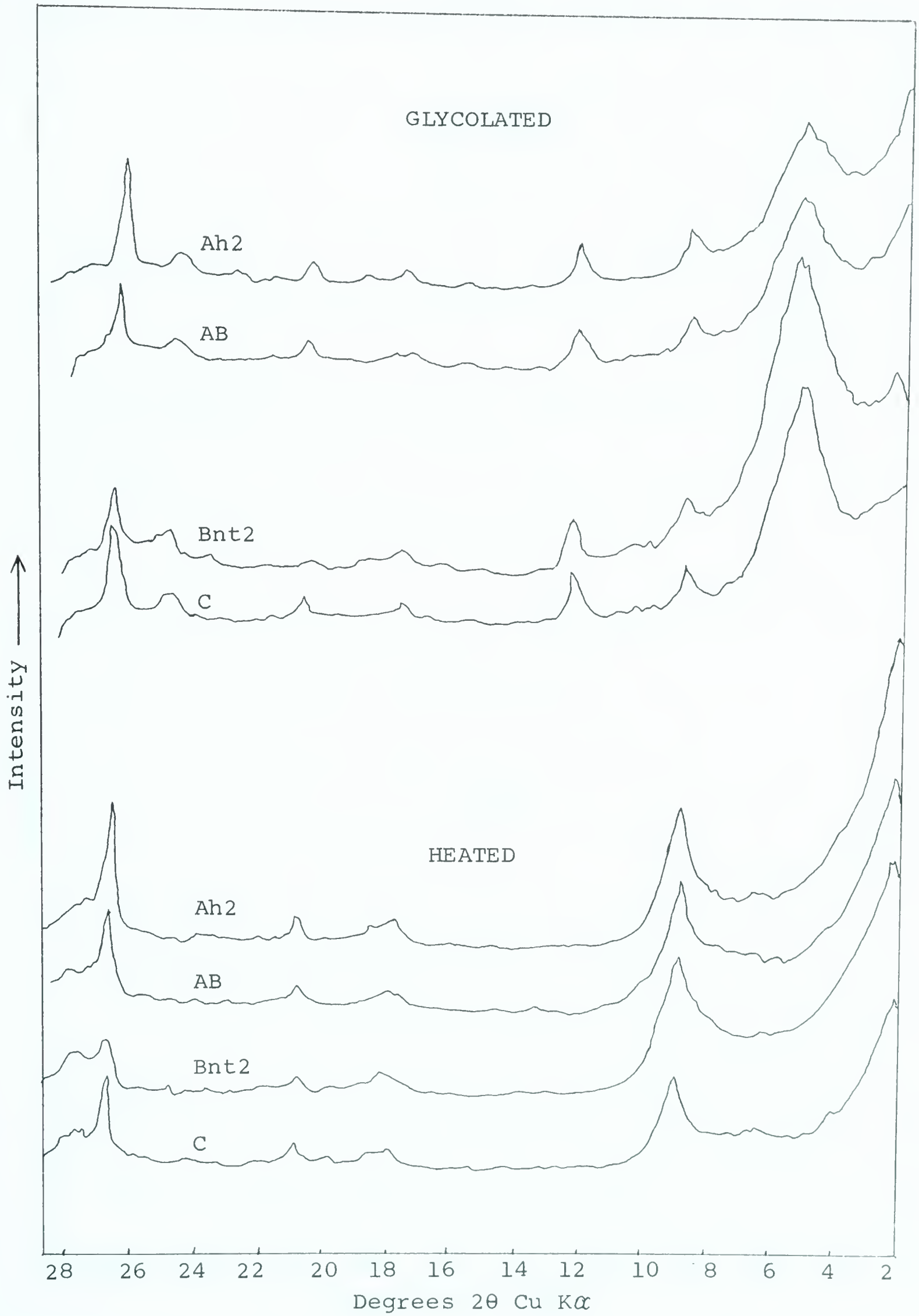

Figure 2. X-ray diffraction patterns of glycolated and heated (550°C.) clay from the major horizons of profile 1.

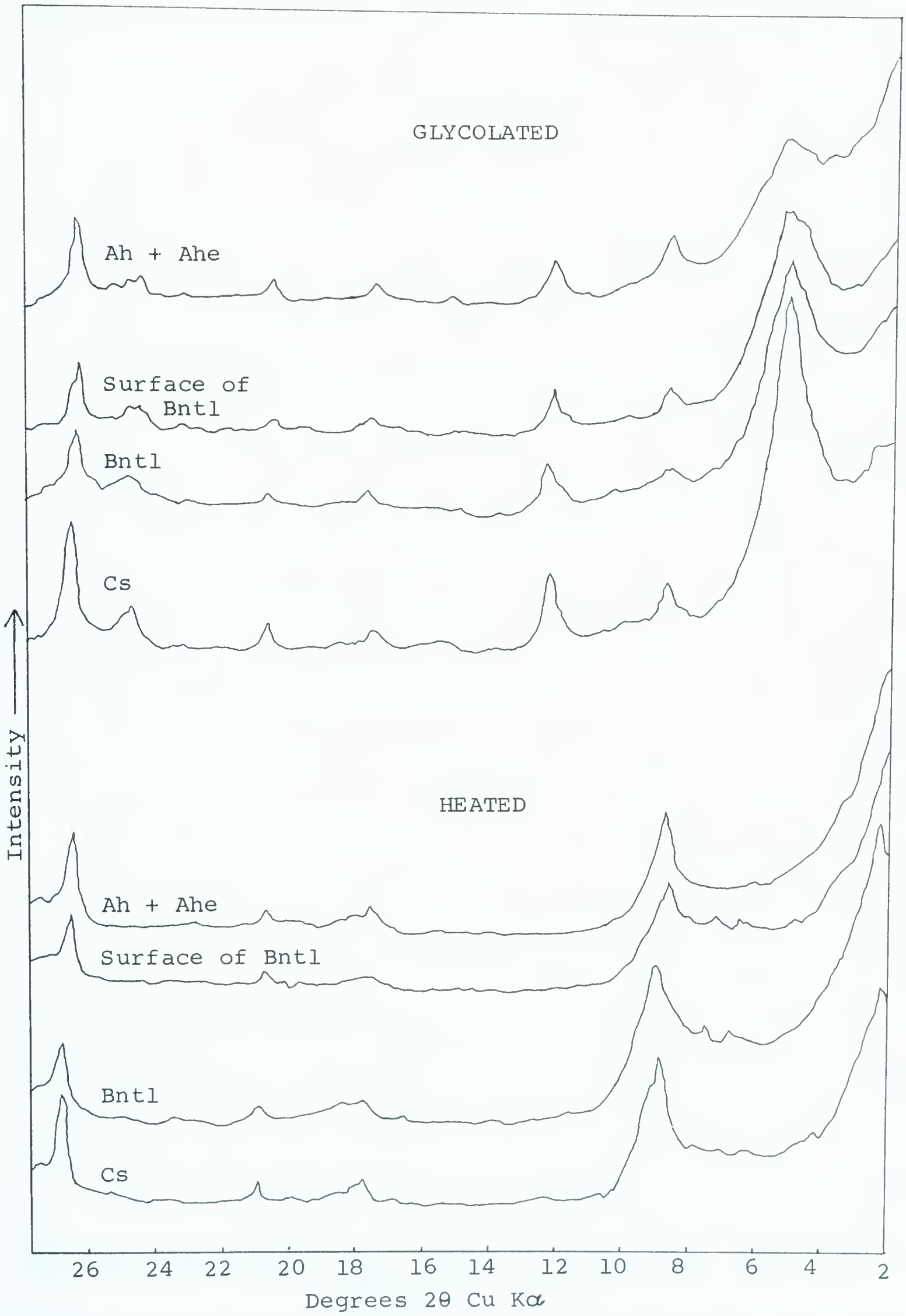

Figure 3. X-ray diffraction patterns of glycolated and heated (550°C.) clay from the major horizons of profile 2.

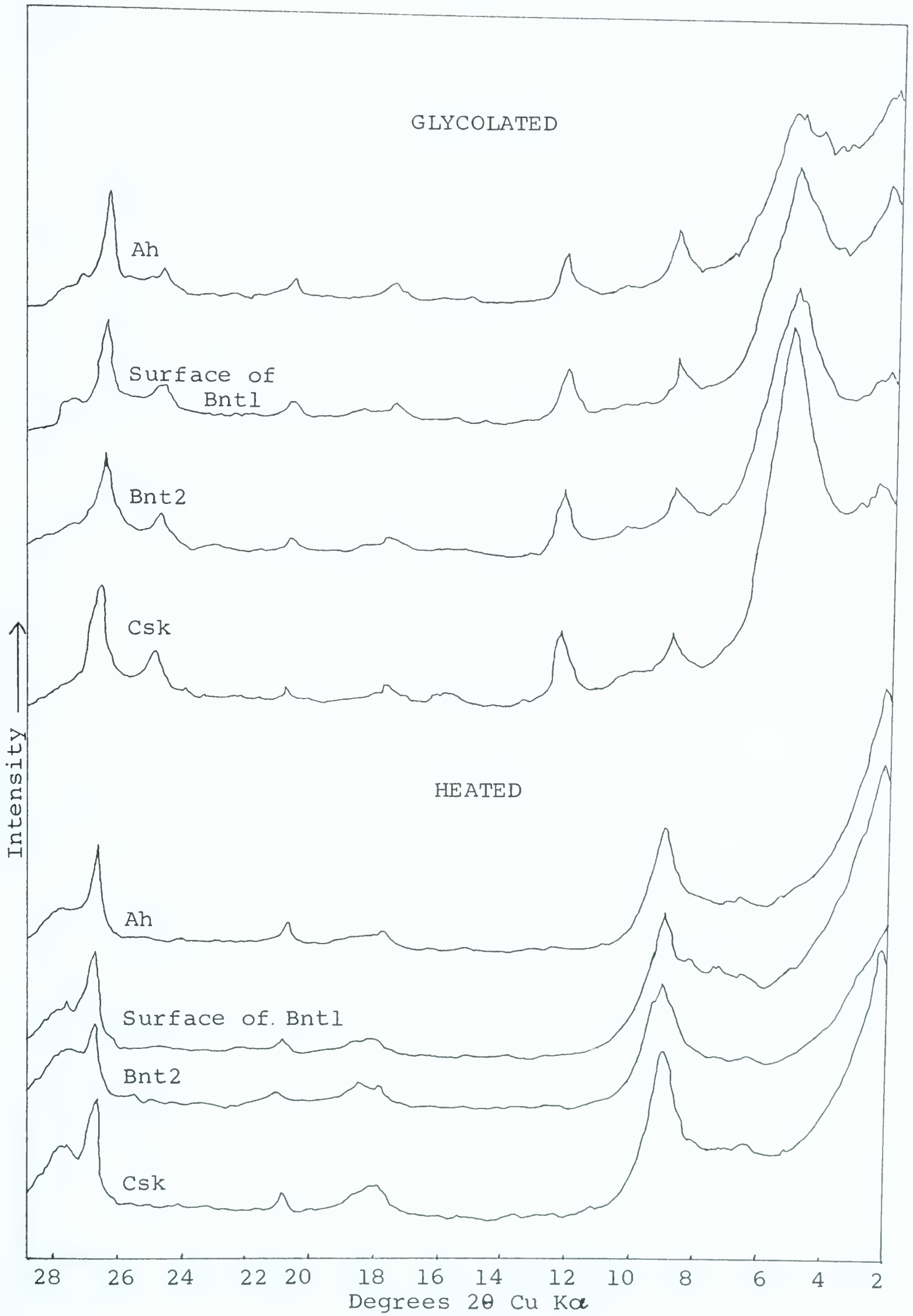

Figure 4. X-ray diffraction patterns of glycolated and heated (550°C.) clay from the major horizons of profile 3.

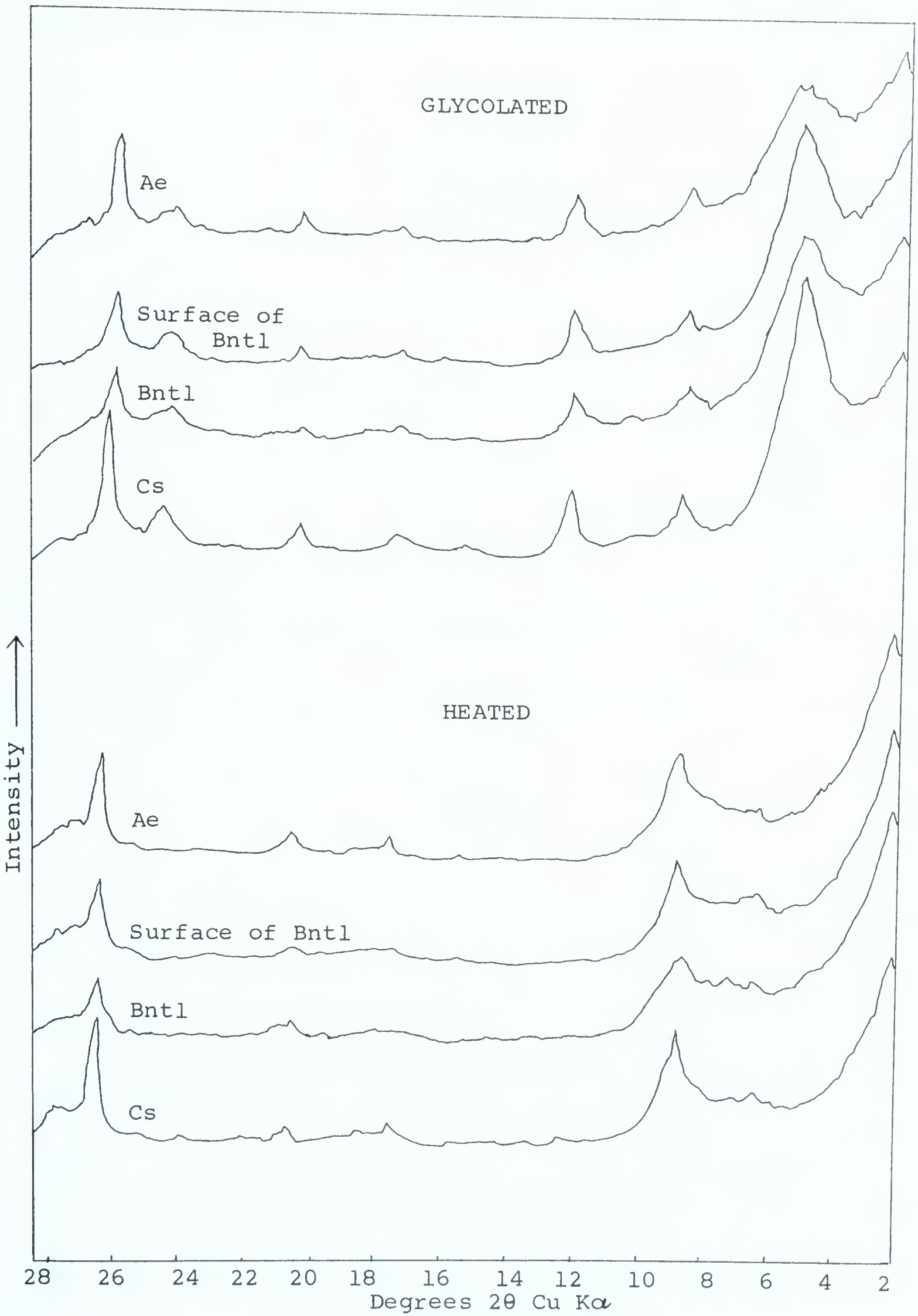

Figure 5. X-ray diffraction patterns of glycolated and heated (550°C.) clay from the major horizons of profile 4.

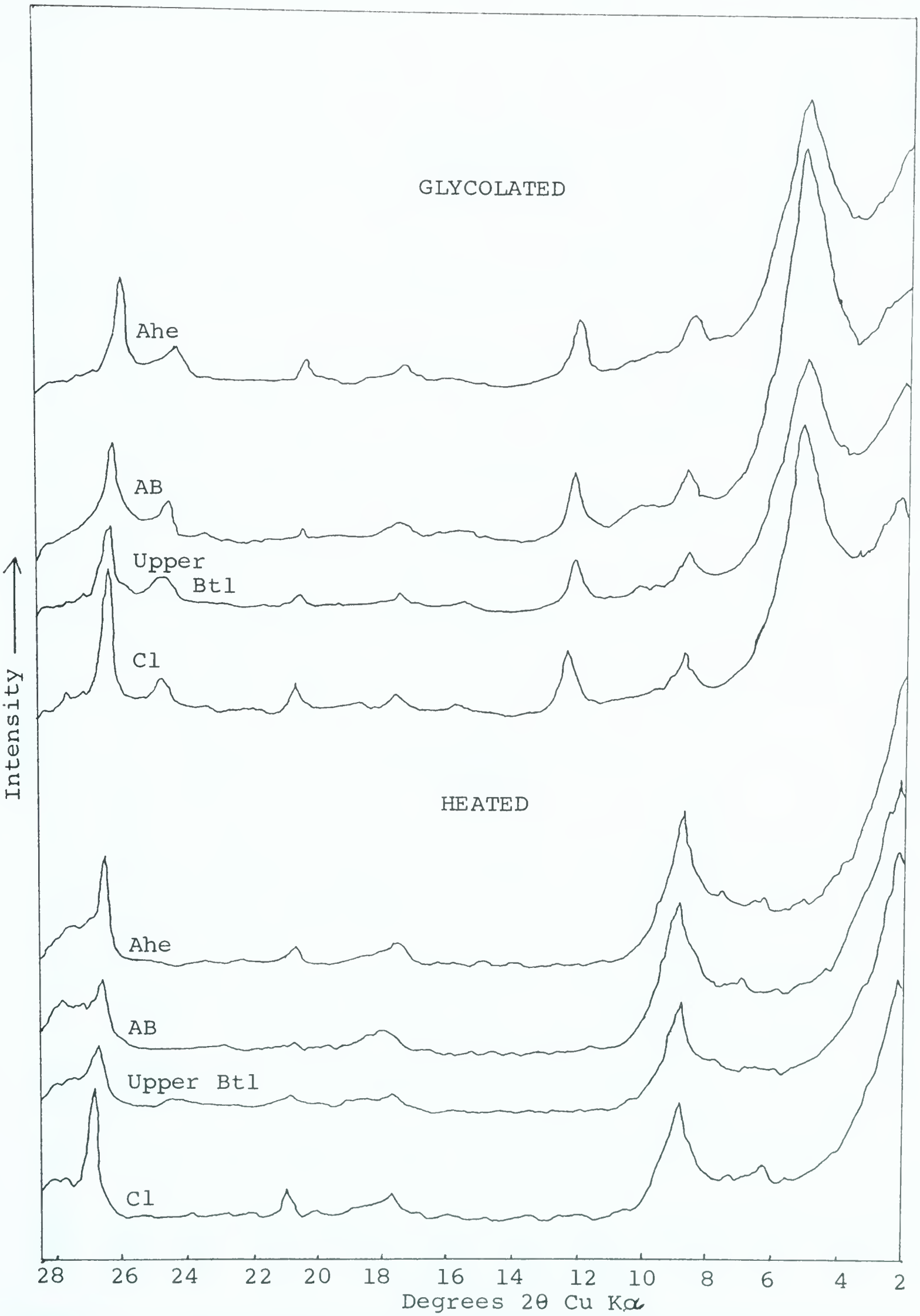

Figure 6. X-ray diffraction patterns of glycolated and heated (550°C.) clay from the major horizons of profile 5.

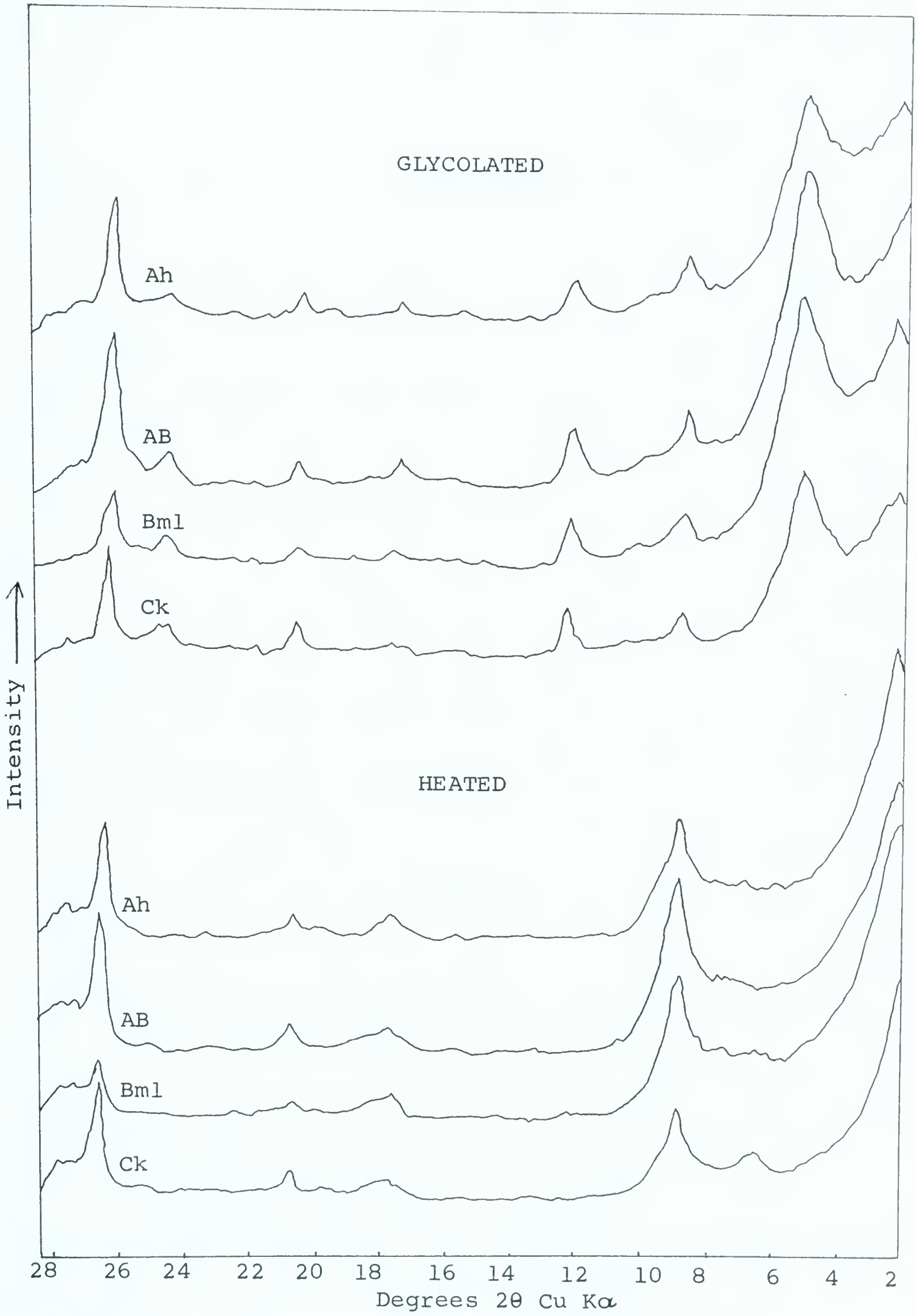

Figure 7. X-ray diffraction patterns of glycolated and heated (550°C.) clay from the major horizons of profile 6.

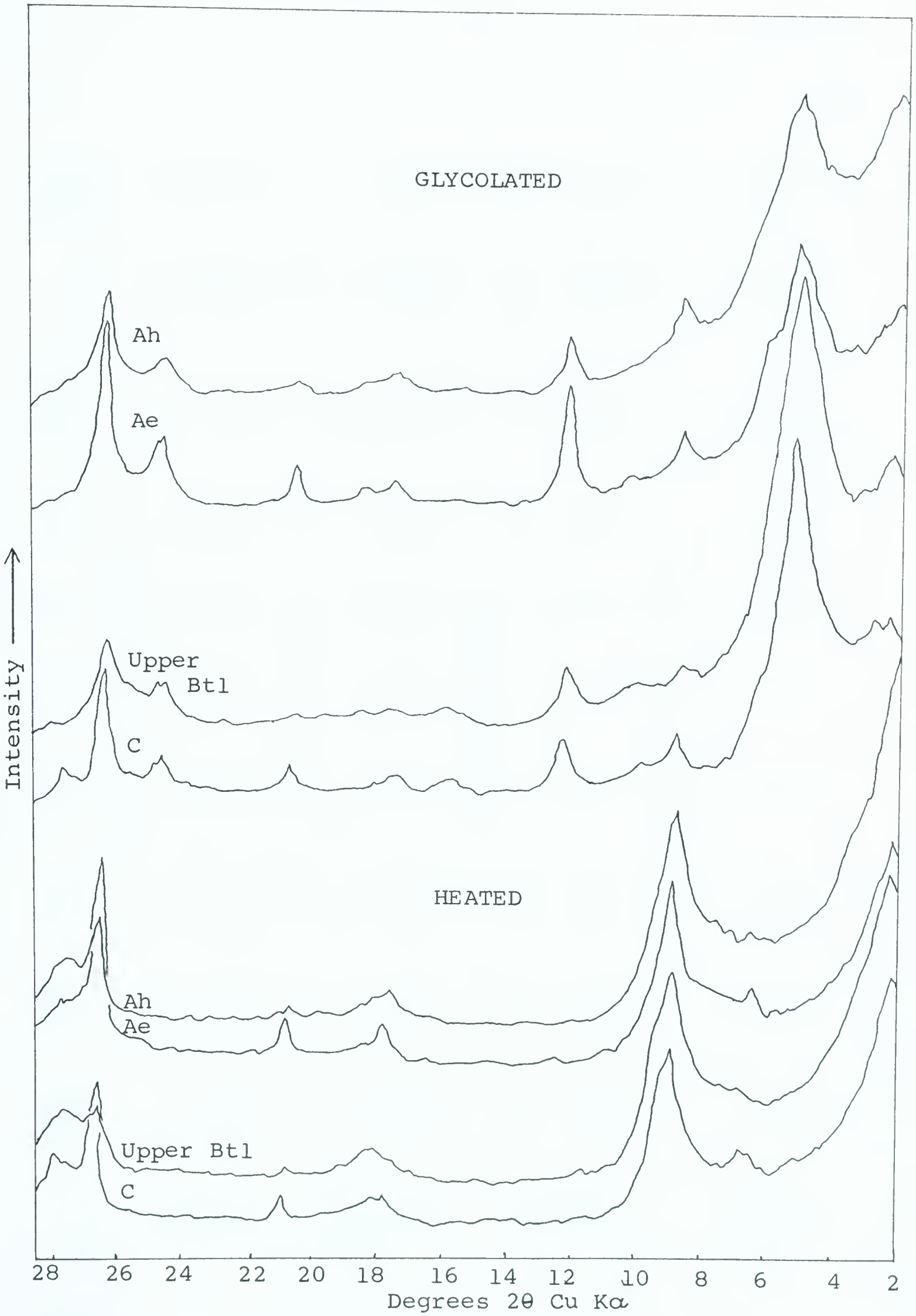

Figure 8. X-ray diffraction patterns of glycolated and heated (550°C.) clay from the major horizons of profile 7.

TABLE XV. Chemical Composition of Clays*

Sample Number	Horizon	Depth in.	SiO_2 %	Al_2O_3 %	Fe_2O_3 %	MgO %	CaO %	K_2O %	Loss on Ignition %	Total	$\frac{SiO_2}{R_2O_3}$
					1. Black Solodized Solonetz						
2	Ah2	3- 7	57.4	26.9	4.0	0.8	0.2	3.2	6.6	99.1	3.3
4	AB	8- 9	53.5	27.3	5.8	1.0	0.2	3.0	7.5	98.3	2.9
6	Bnt2	11-16	51.9	24.2	6.9	1.1	0.6	2.6	11.1	98.3	3.0
10	C	36-42	52.2	24.0	5.2	1.1	0.8	2.8	12.1	98.2	3.2
					2. Black Solonetz						
14,15	Ah+Ahe(3:1)	0- 4	54.8	22.1	4.4	1.0	0.5	2.6	12.4	97.8	3.7
16	Surface of Bnt1	4-10	49.7	23.4	5.8	1.2	0.8	2.3	14.2	97.4	3.1
17	Bnt1	4-10	51.3	26.2	6.0	1.1	0.6	2.3	11.4	98.9	2.9
22	Cs	55-65	54.2	25.1	5.8	1.0	0.5	2.7	8.7	98.0	3.2
					3. Black Solonetz						
25	Ah	0- 3	58.7	24.8	5.3	0.9	0.1	2.8	7.5	100.1	3.4
26	Surface of Bnt1	3- 9	54.4	25.2	6.0	1.2	0.2	2.7	8.4	98.1	3.2
28	Bnt2	9-11	50.8	23.7	6.8	0.9	0.6	2.4	13.3	98.5	3.1
31	Csk	31-45	53.3	24.2	6.1	1.1	0.6	2.6	10.3	98.2	3.2
					4. Black Solodized Solonetz						
37	Ae	4- $5\frac{1}{2}$	55.7	23.0	4.6	1.0	0.2	2.6	10.9	98.0	3.7
39	Surface of Bnt1	6-10	48.1	25.2	6.0	1.5	1.0	2.1	14.8	98.7	2.8
40	Bnt1	6-10	49.4	23.8	6.8	1.1	0.8	2.1	14.5	98.5	3.0
44	Cs	24-31	53.2	23.2	5.5	1.1	0.5	2.4	11.4	97.3	3.4

* Average values of duplicate determinations

TABLE XV. (Continued)

Sample Number	Horizon	Depth in.	SiO_2 %	Al_2O_3 %	Fe_2O_3 %	MgO %	CaO %	K_2O %	Loss on Ignition %	Total	$\frac{SiO_2}{R_2O_3}$
					5. Eluviated Black						
52	Ahe	11-15	53.5	23.8	5.7	0.9	0.7	2.8	10.8	98.2	3.3
53	AB	15-15½	53.4	25.3	7.0	1.0	0.6	2.6	10.2	100.1	3.1
54	Upper Btl	15½-17	52.6	24.6	6.4	0.9	0.5	2.8	11.4	99.2	3.1
59	C1	46-52	57.4	22.2	5.9	0.8	0.4	2.8	8.5	98.0	3.7
					6. Orthic Black (Solodic)						
62	Ah	0- 4	55.8	24.2	5.2	0.9	0.5	3.0	9.5	99.1	3.4
63	AB	4- 9	55.9	22.9	5.6	0.9	0.2	3.1	9.1	97.7	3.6
64	Bm1	9-13	51.3	23.9	6.6	1.1	0.5	3.0	11.5	98.0	3.1
67	Ck	28-41	55.7	24.1	5.2	1.0	0.5	3.0	9.1	98.6	3.4
					7. Eluviated Black						
71	Ah	0- 4	53.1	25.1	6.2	0.9	0.1	3.0	10.9	99.3	3.1
72	Ae	4-10	57.1	23.4	5.0	0.9	0.4	3.2	8.6	98.6	3.7
73	Upper Btl	10-12½	50.4	25.9	7.2	0.9	0.7	2.4	10.8	98.5	2.8
78	C	36-44	53.8	21.2	6.3	0.9	0.8	3.0	9.8	95.8	3.6

The montmorillonite peaks are broader and poorly defined for A horizons. It is believed that the poor definition of peaks, especially in the Ah horizons, is due to organic constituents preventing maximum glycolation and/or possible weathering of the illitic minerals to montmorillonites (White, 1951).

The chemical analysis of the clay fraction of profile 1 (Black Solodized Solonetz) indicates that, in general, silica content decreases with depth in the solum and then increases in the C horizons. A similar pattern is evident for aluminum oxides with the exception of a slight increase in the AB transitional horizon. This may be attributed to the removal of some aluminum oxide from the A horizon during solodization and its deposition in the adjacent (AB) horizon. It is observed that the surface horizons as well as the C horizon have slightly higher contents of silica than the B horizon. This is evidently a reflection of variable proportions of coarse and fine clay in different horizons. Clay-size quartz particles which occur in all profiles, as indicated by X-ray analysis, are more common in the coarse clay fraction than in the fine clay fraction. The B horizons of all profiles have lower contents of silica in comparison to the other horizons. Since the B horizons are relatively low in coarse particles, there is less admixing of the fine-size quartz in their clay fraction. Iron oxide in profile 1 decreases from the Bnt2 horizon to the AB and A horizons and to the C horizon. This suggests a higher montmorillonite content of the Bnt2 horizon. The illite content of this horizon is also low as indicated by poorly defined X-ray diffraction lines and its lower potassium content suggesting some chemical weathering (possibly depotassication) of this mineral.

From the data in Table XV, it is obvious that montmorillonite, which is a dominant mineral in the profiles studied, is fairly rich in aluminum and iron and is low in magnesium. Such clays may be considered to be transitional between the beidellite and nontronite types. The isomorphous substitution in beidellite occurs in the tetrahedral layers and is mainly the replacement of Si^{++++} by Al^{+++} (Grim, 1953). The isomorphism in nontronite is mainly due to the replacement of Al^{+++} by an equivalent amount of Fe^{+++} in the octahedral layer coupled with a low amount of substitution of Si^{++++} by Al^{+++} in the tetrahedral layers. The chemical formulae for these minerals, as suggested by Ross and Hendricks (quoted by Grim, 1953), are as follows:

Beidellite $(OH)_4 (Si_{6.34} \cdot Al_{1.66}) Al_{4.34} O_{20}$

or

$(OH)_4 (Si_6 \cdot Al_2) Al_{4.44} O_{20}$

Nontronite $(OH)_4 (Si_{7.34} \cdot Al_{.66}) Fe^{+3}_4 O_{20}$

or

Nontronite (aluminian) $(OH)_4 (Si_{6.34} \cdot Al_{1.66}) Fe^{+3}_{4.34} O_{20}$

Thus it is clear that the charges in both these minerals are confined to the tetrahedral layers. The isomorphous substitution of equivalent cations (Fe^{+++}) in the octahedral layers of nontronite does not contribute excess charges which are responsible for the cation exchange properties of clays. Therefore, these minerals have relatively lower cation exchange

capacities (Grim, 1953). This fact is borne out by the data on cation exchange capacities (Table XVI) of the profiles studied.

X-ray patterns of profiles 2 and 3 (Black Solonetz) are similar to profile 1 (Black Solodized Solonetz) except that they show more pronounced weathering of illite in the B horizons. This is supported by the chemical analyses (Table XV) which indicate lower contents of potassium oxide in these horizons. The higher silica/sesquioxide ratio of the surface horizon of profile 2 suggests that solodization has been initiated in this profile. Gerasimov (1960) states that a decrease in the silica-sesquioxide ratios with depth in the profile suggests a steady destruction of the clay, that is, a residual accumulation of silica in the upper part of the soil and a downward movement of the products of decomposition (Al_2O_3 and Fe_2O_3). Profile 3 does not show any pronounced solodization, since a relatively uniform distribution of sesquioxides occurs throughout the profile.

The chemical analyses of profiles 1 and 4 (Black Solodized Solonetz) show that the potassium content in the surface horizons is slightly higher relative to the parent material. St. Arnaud and Mortland (1963) stated that such an increase could result from the weathering of other clay minerals with complete removal of the weathering products from the profile or could be due to a process of illitization whereby montmorillonite present in soils fixes potassium and reverts to an illite type of mineral. Bourne (quoted by St. Arnaud and Mortland, 1963) believes that there is a possibility that expanding-type clays, which are more readily dispersed, are translocated in preference to non-expanding types. The lower potassium content,

hence lower illite content, and higher montmorillonite content, as revealed by chemical analyses and surface areas of clays in the Bnt horizons suggest the latter possibility.

The potassium content of the clay fractions of profiles 5 and 6 (Eluviated Black and Orthic Black) are almost uniform throughout the depth of profiles and thus indicate less weathering of illite. Relatively uniform distribution of sesquioxides in profile 6 (Orthic Black) also points out that the solodization has not been very active in this profile. The low sesquioxide content of the surface horizon of profile 5 suggests the downward leaching of the montmorillonite or possibly chemical weathering.

The low content of sesquioxides in the Ae horizon is a noticeable feature of profile 7 (Eluviated Black). This decrease may be attributed to the intense weathering of clay minerals in this horizon. X-ray patterns for the Ae horizon suggest the presence of chlorite and interstratification of chlorite-montmorillonite in relatively larger amounts in this horizon than in other profiles. The intensity of the kaolinite peak (12.4^{o}) in this horizon is also more pronounced. This may be attributed to kaolinization or negative enrichment of this mineral. Since kaolinite is considered to be a relatively stable mineral, the process of solodization may bring about chemical weathering of other complementary minerals and/or eluviation of these minerals from the Ae horizon. The lower contents of potassium of the upper Bt1 horizon suggest weathering of illite and/or the reflection of increased montmorillonite content in

this horizon. Degradation of illite is also indicated by poorly defined X-ray diffraction lines.

Low amounts of calcium and magnesium in the profiles studied suggest the clay minerals are of dioctahedral nature rather than trioctahedral.

Physical and Chemical Properties of Clays

Estimates of different minerals in the clay fraction are reported in Table XVI. Quantitative estimations of the clay mineral composition is based on the data for surface areas, chemical analyses, and cation exchange capacities of total clays. The illite content was determined by assigning all the potassium to illite and assuming illite to have a K_2O content of 10 per cent (Mehra and Jackson, 1959). The illite was assumed to have a cation exchange capacity of 20 me./100 g. (Barshad, 1954) and a surface area of 10 m^2/g. (Jackson, 1956). By assigning these values to illite, the remaining portions of the cation exchange capacity and surface area was assigned to montmorillonite. No value was assigned to kaolinite because of its very low cation exchange capacity and surface area. To estimate the amount of montmorillonite from the cation exchange capacities, it was assumed that its cation exchange capacity is 90 me./100 g. which compares well with the value computed by St. Arnaud and Mortland (1963) for similar minerals and falls within the cation exchange capacity ranges given by various workers (Grim, 1953; Sawhney and Jackson, 1959; Kelley, 1948). To estimate the amount of montmorillonite from the data on surface areas, total surface area was used rather than internal surface area. It was not

TABLE XVI. Some Physical and Chemical Properties of Clays

Sample Number	Horizon	Depth in.	C.Clay %	F.Clay %	Illite	Mont.* (S.A.)	Mont.** (C.E.C.)	Surface Area ($m^2/g.$)***	C.E.C.*** Detd.
				1. Black Solodized Solonetz					
2	Ah2	3- 7	18	15	32[1]	37[1]	34[1]	375	36.8
4	AB	8- 9	16	13	30	45	44	447	45.9
6	Bnt2	11-16	11	30	26	57	55	572	54.9
10	C	36-42	27	24	28	41	37	413	40.0
				2. Black Solonetz					
14,15	Ah+Ahe(3:1)	0- 4	25	14	26	45	40	446	40.9
16	Surface of Bnt1	4-10	14	30	23	50	45	503	45.4
17	Bnt1	4-10	21	42	23	51	51	511	51.2
22	Cs	55-65	29	32	27	43	37	430	39.8
				3. Black Solonetz					
25	Ah	0- 3	25	14	28	45	42	453	43.8
26	Surface of Bnt1	3- 5	18	26	27	41	43	419	44.6
28	Bnt2	5-11	21	32	24	51	51	507	50.9
31	Csk	31-45	35	18	26	44	45	443	43.6
				4. Black Solodized Solonetz					
37	Ae	4- 5½	10	25	26	45	40	458	41.3
39	Surface of Bnt1	6-10	10	24	21	46	43	461	43.3
40	Bnt1	6-10	14	21	21	48	46	482	45.9
44	Cs	24-31	28	29	24	38	34	380	35.8

* Calculated from surface area data

** Calculated from cation exchange data

*** Average of duplicate determinations

[1] Clay minerals expressed in terms of per cent by weight of the total clay fraction

TABLE XVI. (Continued)

Sample Number	Horizon	Depth in.	C.Clay %	F.Clay %	Illite	Mont.* (S.A.)	Mont.** (C.E.C.)	Surface Area ($m^2/g.$)***	C.E.C.*** Detd.
				5. Eluviated Black					
52	Ahe	11-15	23	12	28	45	41	446	42.3
53	AB	15-15½	22	23	26	53	50	534	49.9
54	Upper Bt1	15½-17	27	32	28	47	45	469	46.4
59	C1	46-52	25	23	28	36	32	358	34.8
				6. Orthic Black (Solodic)					
62	Ah	0- 4	29	25	30	40	37	407	39.3
63	AB	4- 9	34	24	31	43	40	426	41.3
64	Bm1	9-13	22	33	30	53	47	536	48.4
67	Ck	28-41	46	30	30	36	30	359	33.3
				7. Eluviated Black					
71	Ah	0- 4	17	9	30	47	42	473	43.9
72	Ae	4-10	14	1	32	30	28	301	31.8
73	Upper Bt1	10-12½	18	38	24	62	57	624	55.9
78	C	36-44	27	23	30	40	36	397	38.8

* Calculated from surface area data
** Calculated from cation exchange data
*** Average of duplicate determinations

considered possible to make exact determination of external surface areas since total clay is composed of particles of variable sizes and the external surface area is a direct function of the size of the particles. In view of the inherent errors involved in the method, no attempt was made to account for the external surface area. The data were considered more appropriate for obtaining a good approximation rather than trying to assess the individual minerals as to their absolute quantity. The surface area for montmorillonite (Arizona), used as a standard, was found to be 997 $m.^2/g$. This value is rather high, although similar results have been reported by other workers (Sawhney and Jackson, 1958) for montmorillonites which have a large proportion of fine-size particles.

On the basis of the data obtained by calculation as well as X-ray analyses, it is evident that the B horizons of all profiles have the maximum amounts of montmorillonite. Illite comprises from 21 to 32 per cent of the clay fraction. This variation, however, does not entirely represent the difference in the illite content of various horizons since the weathered illite may contain less K_2O as a result of possible depotassication. The minimum amount of illite is found in the B horizon of profile 4 (Black Solodized Solonetz) which probably results from weathering. The montmorillonite content calculated from the surface area data is consistently higher than that calculated from the cation exchange capacity data. This may in part result from the fact that the external surface area was not deducted from the total surface area while calculating the percentage of montmorillonite and/or that the montmorillonite

in these soils has an exchange capacity less than 90 me./100 g.

The lowest amount of montmorillonite was found in the Ae horizon of profile 7 (Eluviated Black) indicating the degradation of this mineral and/or possibly its differential eluviation. These results are in accordance with the evidence indicated by X-rays and the chemical analysis of clays in this horizon.

Primary Mineral Analyses

Primary minerals constitute the original source of all chemical elements in soils and make up the greatest proportion of inorganic material in most mineral soils. The sand and silt fractions of soils are comprised almost entirely of primary minerals.

Percentage composition of light, intermediate, and heavy minerals in sand fractions having diameters between 0.15 and 0.10 millimeters is given in Table XVII. The data indicate that the light mineral fraction (sp. gr. < 2.70) comprises the major portion of the total primary minerals. The percentage of light minerals varies from 94.8 to 99.4. The remaining portion of the sand fraction is almost equally distributed between the intermediate (sp. gr. 2.7 to 2.96) and heavy (sp. gr. > 2.96) minerals. In general, the distribution of light minerals in various horizons of the profiles studied is fairly uniform. The B horizons of profiles 2 to 7 show a slight increase in their light mineral content with a corresponding decrease in their intermediate and heavy mineral components. However, these variations are not consistent enough to draw any definite conclusion as to the weathering of these minerals.

TABLE XVII. Percentage Composition of Light, Intermediate, and Heavy Minerals

(in 0.10 - 0.15 mm. Sand Fraction)

Sample Number	Horizon	Depth in.	Mineral Class: Light sp. gr. < 2.70 %	Intermediate sp. gr. 2.70-2.96 %	Heavy sp. gr. > 2.96 %
			1. Black Solodized Solonetz		
2	Ah2	3- 7	98.2	0.78	0.98
4	AB	8- 9	98.4	0.72	0.92
6	Bnt2	11-16	98.0	1.10	0.87
10	C	36-42	98.7	0.35	0.97
			2. Black Solonetz		
14,15	Ah+Ahe (3:1)	0- 4	97.0	2.17	0.84
16	Surface of Bnt1	4-10	97.7	1.32	0.95
17	Bnt1	4-10	98.0	0.82	1.16
22	Cs	55-65	97.8	1.28	0.97
			3. Black Solonetz		
25	Ah	0- 3	97.8	1.54	0.63
26	Surface of Bnt1	3- 9	98.4	0.83	0.81
28	Bnt2	9-11	98.2	1.07	0.77
31	Csk	31-45	97.4	1.59	1.04
			4. Black Solodized Solonetz		
37	Ae	4- 5½	97.9	1.51	0.60
39	Surface of Bnt1	6-10	97.8	1.01	1.09
40	Bnt1	6-10	98.1	1.06	0.82
44	Cs	24-31	97.5	1.43	1.08

TABLE XVII. (Continued)

Sample Number	Horizon	Depth in.	Mineral Class: Light sp. gr. < 2.70 %	Intermediate sp. gr. 2.70-2.96 %	Heavy sp. gr. > 2.96 %
			5. Eluviated Black		
52	Ahe	11-15	94.8	2.82	2.37
53	AB	15-15½	98.4	0.67	0.87
54	Upper Btl	15½-17	98.4	0.76	0.82
59	C1	46-52	95.0	4.05	0.98
			6. Orthic Black (Solodic)		
62	Ah	0- 4	96.9	2.15	0.96
63	AB	4- 9	98.9	0.49	0.57
64	Bm1	9-13	98.4	0.99	0.61
67	Ck	28-41	97.9	1.17	0.92
			7. Eluviated Black		
71	Ah	0- 4	99.2	0.23	0.61
72	Ae	4-10	99.3	0.17	0.52
73	Upper Btl	10-12½	99.4	0.16	0.42
78	Cs	36-44	98.8	0.28	0.93

Light Minerals

In most mineralogical studies of soils attempted to date, light minerals, in spite of their abundance, have been neglected in favour of heavy minerals. However, the identification and chemical composition of these minerals in soils are of great importance when studying soil weathering processes. The constituents of the light mineral fraction, by their variation in amount through the profile, provide a qualitative clue to soil development.

Chemical composition of light minerals separated from the 0.10 to 0.15 millimeter sand fraction is given in Table XVIII. Data on elemental analyses were used to calculate the percentages of potassium and soda-calcic feldspars. Quartz was determined by difference.

The data, in general, indicate that there is no major variation in the distribution of potassium feldspar in the profiles studied. However, a slight decrease of this mineral in the Ae and upper Bt1 horizon of profile 7 (Eluviated Black) does indicate some weathering, probably during solodization. Low contents of potassium feldspar in the surface horizon of profile 2 (Black Solonetz) suggest the dissolution of this mineral as a result of the initiation of the solodization process.

The distribution pattern of soda-calcic feldspar in these soils suggest more pronounced weathering of this mineral in comparison to the potassium feldspar. Their low contents in the surface horizons point out that the dissolution of these

TABLE XVIII. Chemical Composition of Light Minerals*

(in 0.10 -0.15 mm. Sand Fraction)

Sample Number	Horizon	Depth in.	Al_2O_3 %	Fe_2O_3 %	CaO %	MgO %	Na_2O %	K_2O %	SiO_2 %	K-Feldspar %	Na-Ca-Feldspar %	Quartz %
					1. Black Solodized Solonetz							
2	Ah2	3- 7	7.46	1.00	0.69	0.16	1.20	1.10	88.39	7	14	79
4	AB	8- 9	7.10	1.40	0.48	0.25	1.71	1.33	87.73	8	17	75
6	Bnt2	11-16	8.00	1.14	0.48	0.30	2.39	1.58	86.11	9	22	69
10	C	36-42	9.74	0.91	1.04	0.16	2.11	1.32	84.72	8	22	70
					2. Black Solonetz							
14,15 16	Ah+Ahe(3:1) Surface of Bnt1	0- 4 4-10	3.55 7.58	1.08 2.08	0.70 0.47	0.13 T**	0.83 1.94	0.73 1.10	92.98 86.76	4 7	11 19	85 74
17	Bnt1	4-10	7.72	2.42	0.52	T**	2.40	1.28	85.56	8	23	69
22	Cs	55-65	7.19	0.54	0.29	0.14	2.63	1.29	87.92	8	24	68
					3. Black Solonetz							
25	Ah	0- 3	7.68	3.30	0.72	0.26	1.40	1.23	85.41	7	16	77
26	Surface of Bnt1	3- 9	6.89	0.90	0.86	0.13	1.54	1.16	88.52	7	17	76
28	Bnt2	9-11	6.94	2.51	0.66	0.18	1.44	1.18	87.09	7	16	77
31	Csk	31-45	7.48	0.92	2.07	0.36	1.64	1.34	86.20	8	24	68
					4. Black Solodized Solonetz							
37	Ae	4- 5½	8.07	3.14	0.43	0.42	1.41	1.26	85.27	8	14	78
39	Surface of Bnt1	6-10	6.75	1.89	0.47	0.34	1.67	1.30	87.58	8	16	76
40	Bnt1	6-10	7.39	2.27	0.68	0.17	1.32	1.20	86.97	7	15	78
44	Cs	24-31	6.85	0.52	1.05	0.28	1.45	1.26	88.59	8	18	74

* Average values of duplicate determinations

** Less than 0.1 per cent

TABLE XVIII. (Continued)

Sample Number	Horizon	Depth in.	Al_2O_3 %	Fe_2O_3 %	CaO %	MgO %	Na_2O %	K_2O %	SiO_2 %	K-Feldspar %	Na-Ca-Feldspar %	Quartz %
					5. Eluviated Black							
52	Ahe	11-15	6.31	0.68	0.71	0.13	1.54	1.27	89.36	8	17	75
53	AB	15-15½	6.36	1.44	0.49	0.32	1.40	1.32	88.67	8	14	78
54	Upper Bt1	15½-17	6.50	1.72	0.50	0.35	1.46	1.28	88.19	8	15	77
59	C1	46-52	6.00	1.23	1.29	0.40	1.60	1.28	88.20	8	20	72
					6. Orthic Black (Solodic)							
62	Ah	0- 4	8.58	2.62	0.56	0.57	1.44	1.60	84.63	9	15	76
63	AB	4- 9	9.04	3.20	0.69	0.56	1.40	1.59	83.52	9	15	76
64	Bm1	9-13	9.17	2.98	0.75	0.48	1.53	1.50	83.59	9	17	74
67	Ck	28-41	6.27	1.44	0.80	0.48	2.05	1.12	87.84	7	21	72
					7. Eluviated Black							
71	Ah	0- 4	6.25	0.90	1.72	0.49	1.26	1.30	88.08	8	19	73
72	Ae	4-10	5.40	0.38	1.10	T*	1.20	1.10	90.82	7	16	77
73	Upper Bt1	10-12½	4.87	0.32	1.05	0.14	1.15	1.11	91.36	7	15	78
78	Cs	36-44	5.70	0.55	2.00	0.80	1.28	1.35	88.32	8	21	71

* Less than 0.1 per cent

minerals has occurred as a result of weathering. Weathering appears to be more severe in calcium feldspar than in sodium feldspar. It is interesting to note that there is an abrupt decrease in the contents of soda-calcic feldspars of the Ae and upper Btl horizons of profile 7 (Eluviated Black). This fact together with the decrease of the potassium feldspar component suggests that intense weathering accompanied the solodization in this profile.

The distribution pattern of quartz in these soils indicates that the percentage of this mineral is relatively high in horizons that have undergone solonetzic degradation (solodization). Since quartz is a stable mineral component of the light mineral fraction, its increase may be attributed to negative enrichment.

On the basis of results reported in this study, it is suggested that among the profiles studied most severe solodization has occurred in profile 7 (Eluviated Black).

CONCLUSIONS

From the foregoing discussion, it is evident that the soils under study differ markedly from one another in the degree and mode of their pedogenic development.

The clay maxima in the B and upper C horizons of Black Solonetz (profiles 2 and 3), as pointed out previously, are attributed to variable dispersion together with a limited amount of illuviation from the surface horizons. High amounts of soluble salts in the lower horizons keep the clays in a flocculated state thus reducing their movabilities to a considerable extent. These profiles contain higher contents of soluble salts as compared to Solodized Solonetz (profiles 1 and 4) indicating the difference in the degree of their pedogenic development. Sodium sulphate is the dominant salt in the Black Solonetz as well as Black Solodized Solonetz.

Surface horizons of Black Solonetz contain considerable amounts of exchangeable sodium which suggests that these soils are in their initial stages in the evolution of Solonetzic soils. However, a higher content of soluble silica, a lower content of sesquioxides in the clay fraction and in the primary minerals, a higher silica/sesquioxide ratio in the clay fraction, as well as some evidence of illite weathering, in the surface horizon of the Black Solonetz (profile 2) suggests that solodization is beginning. The horizon of salt accumulation in the case of Black Solonetz as well as Solodized Solonetz (profiles 1 and 4) suggest that the soils in this area have been subjected to resalinization resulting from upward movement of moisture.

It is of some significance that organic carbon and nitrogen in the Ahe and Ae horizons of the Solodized Solonetz (profiles 1 and 4) is much higher than in the underlying B horizons. Mineralogical data, however, suggest only slight weathering of clay minerals and of soda-calcic feldspars.

A higher content of exchangeable aluminum in the Ae horizon of profile 4 (Black Solodized Solonetz) suggests that the solodization is more severe in this profile than in profiles 1, 2, and 3. Clay mineral analyses suggest that the Black Solodized Solonetz at site 1 has a higher content of montmorillonite in its B horizons as compared to the Black Solodized Solonetz at site 4 and the Black Solonetz at sites 2 and 3. Preferential physical movement of this mineral accompanied by a slight chemical degradation is suggested in all these profiles. The degradation appears to be relatively more intense in the Black Solodized Solonetz of site 4. This is indicated by the lower content of montmorillonite as well as illite. Weathering of illite is evident from poorly defined X-ray diffraction patterns at 10 Å spacings.

The profile at site 7 (Eluviated Black) differs markedly from the other profiles studied. Soluble salts occur at a considerable depth and magnesium is the dominant cation in the B horizon. The prevailing conditions at this location have favoured the replacement of the monovalent sodium cation by the divalent magnesium cation on the exchange complex as explained previously. A low content of organic matter and a high content of exchangeable aluminum in the eluviated (Ae)

horizon suggest that this profile has undergone severe solodization. Mineralogical data suggest that an increase in kaolinite has occurred, probably as a result of preferential translocation of expanding-type clays (montmorillonites) and the degradation of illite. The preferential translocation of montmorillonites is evident from the fact that its content is lowest in the Ae horizon with a corresponding accumulation in the adjacent (upper Bt1) horizon. The physical movement of undecomposed clay has been demonstrated by many workers (Ehrlich and Smith, 1958; Antipov-karataev, 1960) in similar soils. However, the data obtained in this study suggest that physical movement as well as chemical transformation of the clay is responsible for the disappearance of the clays from the eluviated horizon. Dissolution of soda-calcic feldspars is also evident. This suggests that the profile at this site has undergone the most intensive weathering among the profiles studied.

The Eluviated Black soil at site 5 differs markedly from the Eluviated Black soil at site 7. While profile 7 has undergone severe solodization, as mentioned above, profile 5 shows little weathering of clay as well as primary minerals. There is very little illuviation of the clay from the surface horizons to the lower horizons in its solum. Soluble salts and exchangeable sodium is negligible throughout the entire depth of the profile and there is no horizon of intense weathering in the solum. It appears, therefore, that this profile was not subjected to strong solodization. Rather mild conditions were likely prevalent where the fluctuation of moisture highly

charged with sodium cations has solublized some organic matter from the surface horizons and leached it downward thus giving the upper solum a degraded appearance.

The soil profile at site 6 was recognized in the field as an Orthic Black by its typical morphology of this Great Group. Laboratory studies indicated that this soil contains a high content of soluble salts in which magnesium is the dominant cation. Exchangeable magnesium in the B horizon exceeds 50 per cent of the total exchangeable cations. In view of its chemical criteria, this profile may be considered similar to the magnesium-Solonetz in Manitoba.[1] However, in spite of its higher magnesium content, the B horizon does not show the morphological characteristics of Solonetzic soils as described by the National Soil Survey Committee of Canada (1963). This profile was, therefore, called Solodic for want of a better name. It appears that conditions similar to those at site 7 may have prevailed at this location. Both the profiles are associated with the surrounding Solonetzic soils which contain high contents of sodium salts. Also, both the profiles occupy level to depressional positions at higher elevations which may have been a factor favouring the removal of sodium salts according to the phenominon already stated. The removal of sodium salts, however, likely differs in these two profiles. It appears that resalinization from moisture rise in the case of profile 6 was limited and the removal of the initial sodium

[1] Unpublished data by the National Soil Survey Sub-committee on Solonetzic soils.

saturation on the exchange complex was fairly rapid. Thus, only limited degradation and solonetzic development has occurred.

Considering the various aspects of the present study, as described above, these profiles may be arranged as follows in order of their pedogenic development:

Profile 7 > profile 4 > profile 1 > profile 2 > profile 3 > profile 5 > profile 6.

SUMMARY

The general trend in the studies of Solonetzic soils over the past several years has been towards an understanding of the characteristics and cultural aspects of these soils rather than their genesis. Little work has been done in the study of mineralogical weathering as related to the pedogenic processes concerned in the evolution of these soils. The objectives of this investigation were (1) to assess the extent and the nature of mineralogical weathering active in the major horizons of some Solonetzic soils of Alberta in relation to their genesis, (2) to elucidate some of the mechanisms involved in the formation and degradation of solonetzic B horizons, and (3) to clarify some of the contradictory opinions held by previous workers as they relate to the genesis of Solonetzic soils.

Seven profiles selected for this study included two Black Solonetz, two Solodized Solonetz, two Eluviated Chernozems, and one Orthic Black. Physical, chemical, and mineralogical analyses were conducted. The results obtained from these analyses are summarized as follows:

1. The B horizons of Solonetz and Solodized Solonetz soils are relatively higher in clay content than the remaining horizons. This has likely resulted, at least in part, from variable dispersion of clays under the influence of sodium saturation. A large portion of the fine clay fraction in these horizons is formed as a result of comminution of coarse particles. The illuviation of fine clay in these

profiles is very limited. A marked illuviation, however, was observed in the Eluviated Black soil at site 7.

2. Higher clay content was found in the horizons of high salt accumulation. The salts in these horizons greatly reduce the movability of the clay colloids.
3. Sodium sulphate is the dominant salt in the profiles studied except profiles 6 and 7 where magnesium sulphate predominates.
4. Soils at site 1, 2, 3, and 4 meet the chemical as well as morphological criteria of Solonetzic soils. The maximum exchangeable sodium percentage in the B horizons of these soils varies from 14.3 to 40.6. Profiles 5 and 7 are recognized as Eluviated Black of the Chernozemic order. Profile 6 does not exhibit the morphology but does have the chemistry of the Solonetzic soils owing to its high exchangeable magnesium content in the B horizon.
5. The carbon to nitrogen ratio in the soils studied ranges from 7 (in the C horizon of profile 1) to 19 (in the Ae horizon of profile 7). On the basis of the carbon to nitrogen ratios, all profiles possess Chernozemic Ah horizons.
6. A considerable portion of exchange acidity is contributed by the hydrogen released by the hydrolysis of exchangeable aluminum ions. Maximum acidity due to exchangeable aluminum occurred in the Ae horizon of profile 7. In general, exchangeable aluminum is fairly high for horizons which have undergone solodization.

7. Two methods ($BaCl_2$-Trieth., pH 8.1 and $Ba(C_2H_3O_2)_2$, pH 7.0) for measuring the exchange acidity are compared. High values for exchange acidity in the surface horizons, which are high in organic matter, are attributed to the dissociation of -COOH and -OH groups from the organic complex at the higher pH of the $BaCl_2$-Trieth. method. Similar results have been reported by Pawluk and Carson (1963).
8. In general, there is a gradual increase in the content of free iron with increase in depth of the profiles studied. The amount of aluminum oxide in various horizons was small although a higher content was observed in the more acid horizons. The content of free silica is relatively high in the surface horizons and there is a gradual decrease with downward progression in the solum. A relatively high content of soluble silica in the surface horizon of profile 2 suggests the initiation of the solodization process in this profile.
9. X-ray analyses indicate montmorillonite as the dominant clay mineral while illite and kaolinite are next in abundance except in the case of the Solodized (Ae) horizon of profile 7 where kaolinite almost equals montmorillonite. Traces of chlorite and interstratified chlorite-montmorillonite are also present.
10. The lower illite content and higher montmorillonite content in the B horizons, as revealed by chemical analyses and surface areas of clays, suggest the preferential translocation of montmorillonite. The degradation of illite in the solodized (Ae) horizons is indicated by poorly

defined spacing on X-ray diffraction patterns. Thus, physical translocation as well as chemical transformation of the clay minerals during the process of solodization is suggested.

12. Chemical analyses indicate that clay minerals in these soils are rich in aluminum and iron but are low in magnesium. It is suggested that these clays are transitional between the beidellite and nontronite types and are dioctahedral.

13. Analyses of light minerals, which comprise the major portion of the total primary minerals, indicate a slight weathering of soda-calcic feldspars in the sola of the profiles studied. On the basis of these analyses, it is concluded that most intensive weathering has occurred in the Ae and upper Bt1 horizons of profile 7.

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